Extreme health sensing: the challenges, technologies, and strategies for active health sustainment of military personnel during training and combat missions

Mark Buller[ab*], Alexander Welles[a], Odest Chadwicke Jenkins[b], Reed Hoyt[a]
[a]United States Army Research Institute of Environmental Medicine, Natick, MA USA 01760-5007;
[b]Dept. of Computer Science, Brown University, 45 Prospect St., Providence, RI USA 02906;

ABSTRACT

Military personnel are often asked to accomplish rigorous missions in extremes of climate, terrain, and terrestrial altitude. Personal protective clothing and individual equipment such as body armor or chemical biological suits and excessive equipment loads, exacerbate the physiological strain. Health, over even short mission durations, can easily be compromised. Measuring and acting upon health information can provide a means to dynamically manage both health and mission goals. However, the measurement of health state in austere military environments is challenging; (1) body worn sensors must be of minimal weight and size, consume little power, and be comfortable and unobtrusive enough for prolonged wear; (2) health states are not directly measureable and must be estimated; (3) sensor measurements are prone to noise, artifact, and failure. Given these constraints we examine current successful ambulatory physiological status monitoring technologies, review maturing sensors that may provide key health state insights in the future, and discuss unconventional analytical techniques that optimize health, mission goals, and doctrine from the perspective of thermal work strain assessment and management.

Keywords: physiological status monitoring, estimating health state, situational awareness, thermal work strain assessment.

1. INTRODUCTION

The current US Army Field Manual on Operations[1] states that “Soldiers require an expeditionary mindset to prepare them for short-notice deployments into uncertain, often austere environments” and that “expeditionary capability is the ability to promptly deploy combined armed forces worldwide into any operation environment and operate effectively upon arrival.” Deployments in countries such as Afghanistan, where altitude ranges from 258-7492 m above sea level[2] and daily temperatures vary between 45°-50°C in summer and -24° to -8°C in winter[3], embody the “austere” operational environment in which soldiers are expected to perform. The environmental stress experienced by the soldier is further exacerbated by personal protective equipment (PPE) such as body armor, CBRN (chemical, biological, radiological, nuclear) suits, and loads (including equipment and clothing) averaging 52% of body weight[4] (fig. 1). Monitoring weather and using work rest tables is one method by which the effects of work, environment, and clothing on physiologic strain can be managed. Current military heat injury prevention guidelines[5] use environmental heat categories based on the wet-bulb globe temperature (WBGT) index[6,7] to set mission work-rest schedules and guide water consumption. Despite having reduced the overall incidence of heat illness[8,9], the WGBT index in combination with military guidance tables has not eliminated all cases of heat illness[10] and remains a limited tool for predicting overall physiological strain and a soldier’s capability to accomplish mission goals.

In order to adequately monitor a soldier’s physiology, multiple aspects of health state must be estimated from unconventional outputs using a variety of body worn sensors. Variance among individuals can account for differences in physical performance in stressful environments (e.g., hydration, heat stress, and metabolic deficit can exasperate sleep deprivation and impair cognitive function). Data recorded by a single device or sensor type may only provide a

---

[*] mark.j.buller@us.army.mil, mbuller@cs.brown.edu

Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for
Homeland Security and Homeland Defense IX, edited by Edward M. Carapezza, Proc. of SPIE
Vol. 7666, 766610 · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.853101

"keyhole" view of the soldier's overall health state and incorrectly indicate or predict physiological states. Therefore, it is necessary to integrate multiple sensor types to provide contextualized health state data from which leaders can better predict future performance and make informed decisions on how to accomplish mission goals. Estimating health state in an ambulatory setting encompasses three broad areas: (1) sensor noise management, (2) health state algorithms, and (3) optimal decision making. This paper examines these three areas from the perspective of thermal work strain assessment.

Figure 1. Examples of stressful environments and PPE including A) fully encapsulating chemical biological suits, B) body armor in high heat (Iraq), C) winter gear, and D) rescue gear in an enclosed space.

2. CHALLENGES

The military operational environment poses unique challenges for the development of individual health sensing systems. (1) Sensors are constrained by size, power, and wearability. For example: as a device needs more power its size and weight will increase; as size increases, acceptability generally decreases. The excessive load carried by the foot soldier has been an issue for many years[11] and continues today, with loads greater than 90 lbs not uncommon[12]. Any additional item that a warfighter is required to carry requires justification in terms of cost, weight, and overall benefit. If it is small, light, and provides the soldier with a tangible benefit it will more likely be accepted. (2) There are few medical grade physiological sensors that function well during field use. Many medical sensors that rely on wires and adhesives to function, and are intended for patients who are supine and stationary. Sensors of this kind often rely on the availability of unlimited power and processing capability to function and possess limited ability to manage motion artifact. However, signal artifact and error are exacerbated in the field and can include rapidly changing baselines, signal clipping, dropouts, and movement noise. Compounding the problem, classical adhesive sensor electrodes may not stay attached during sweating and are generally not acceptable to foot soldiers[13]. (3) Finally, as addressed in the algorithm section below, most physiologic parameters needed for health state estimation are difficult to measure accurately in most settings much less an ambulatory one.

3. TECHNOLOGIES – SENSORS

The concept of directly monitoring the physiology of free living individuals draws from a long line of forward-looking research beginning in the early 20th century. In 1906 Nathan Zuntz, a German physiologist, created a portable dry gas measuring device capable of measuring expired gas volume to better aid his studies on the physiological effects of high altitude[14]. In 1902 Willem Einthoven, a Dutch physician, published the first accurate electrocardiogram data using a modified wire coil galvanometer[15] and in 1928 the first portable version (weighing 22.7 kg and powered by a 6-volt automobile battery) was created by the Sanborn Company[16]. Accelerometers made their debut when McCollum and Peters developed a resistance-bridge accelerometer based on a Wheatstone half-bridge[17] which was commercialized in 1923 for use in bridges, dynamometers, and aircraft[18]. Initial models weighed around 450 grams and measured about 2 x 5 x 22 cm.

At the close of the 20th century, individual sensors were light and wearable enough to be incorporated into systems that monitored a number of physiological parameters. Prototype systems included: (1) Yale University and NASA's joint test of a physiological monitoring system capable of monitoring heart rate, accelerometry, skin and core body temperature (Tskin and Tcore respectively) during an ascent of Mt. Everest[19]; (2) the monitoring of Boston Marathon runners by Massachusetts Institute of Technology (MIT) students during a project named Marathon Man[20]; and (3) the development of an ingestible core thermometer pill (sponsored by NASA and the U.S. Army)[21], and the U.S. Army's field testing of an integrated sensor system that measured motion, heart rate, core body temperature, pedometry, and geo-location during military training events[22]. Although nascent, these systems demonstrated the potential value of monitoring multiple physiological parameters.

Today a range of, ambulatory physiological status monitoring (PSM) systems are available commercially from a variety of companies. PSM Technology can be loosely stratified into three overlapping commercial sectors: fitness and athletic training, healthcare, and emergency services.

3.1 Fitness and athletic training

Fitness and training products include heart rate monitors, global positioning systems, physical activity monitors, and pedometers produced by a variety number of companies (e.g., Polar, Kempele, Finland; Garmin, Olathe, KS; ActiGraph, Pensacola, FL; BodyMedia, Pittsburgh, PA; Omron, Kyoto, Japan; Nike, Inc., Washington County, OR; Timex Group USA, Middlebury, CT; Philips, Amsterdam, Netherlands). Generally these devices are worn during exercise or everyday activity and integrate sensor data (e.g., HR, activity counts, distance traveled, time elapsed) with user input (e.g., gender, age, weight, stride length, resting HR, maximal HR) to estimate energy expenditure and or physical activity using proprietary algorithms. Although small, unobtrusive, and non-invasive, fitness and athletic PSM devices do not often meet clinical standards and provide approximate measurements. Evaluations against standard measures of energy expenditure using either indirect calorimetry or double labeled water[23,24] have found that many pedometers and accelerometer-based physical activity monitors accurately detect physical activity, but often underestimate energy expenditure[25,26]. Figure 2, depicts typical fitness devices that can be purchased today.

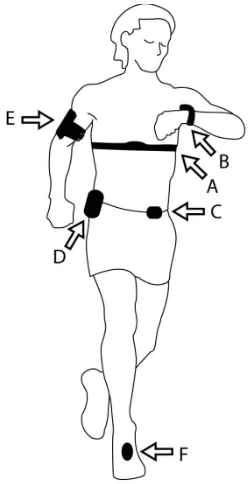

Figure 2. Various fitness physiological status monitoring devices commercially available for running and walking including: (A) heart rate monitor with (B) watch display; (C) waist and (F) foot mounted pedometers; (E) arm mounted triaxial accelerometer; and (D) smart phone/GPS unit.

3.2 Medical and home health care

PSM devices designed for healthcare applications are used both at home and in hospital settings. These devices face greater technological constraints and challenges than those within the fitness and training field as the data they provide are held to greater standards of accuracy (e.g., FDA certification). Widespread use of PSM within healthcare began with clinical use of the Holter monitor the 1960s[27]. The Holter is a body worn ambulatory electrocardiography device measuring about 11 x 7 x 3 cm and capable of continuously recording a patient's electrocardiogram (ECG) or electroencephalograph (EEG) via adhesive gel electrodes for 24-48 hours (still in use today). Similar to the Holter monitor, other portable medical devices designed for use at home or in the hospital (e.g., pulse oximeters/SpO_2 monitors, HR monitors, glucose monitors, automated blood pressure (BP) cuffs, and accelerometer-based fall detection devices) often measure only one or two physiological parameters which provide valuable indicators for a patient with a known pathology but which might otherwise miss a different disease[28]. Devices such as the ProPaq LT (Welch Alllyn Inc, Onondaga County, NY), the CAS 750 (CAS Medical Systems, Inc., Branford, CT), and the MP30 (Philips, Amsterdam, Netherlands), all of which are "portable" (weighing between 2.2 and 5.8 kg) and battery powered (3-24 hours battery life depending on settings), are capable of monitoring and recording ECG, HR, SpO_2 (blood oxygen saturation), and blood pressure. Each device uses conventional adhesive ECG electrodes, a blood pressure cuff, a pulse oximeter, and software that includes noise reduction algorithms. These devices however, require trained medical personnel to interpret sensor data and determine patient health.

Development of medical PSM devices for ambulatory use has led to the integration of sensors with wearable textiles and or modules containing sensors and processing electronics. The WEALTHY system[29], the VivoMetrix LifeShirt[28], the MagIC system[30], the Smart Vest[31], and the MyHeart project[32] combine sensors for multiple physiological parameters (ECG, respiratory rate, SpO_2, etc.) with textile garments to reduce bulk and discomfort, skin irritation due to electrode gels, inconvenient wiring, sensitivity to motion artifact, and increase overall user comfort[28,31].

The medical PSM networking projects (e.g. *Human++*[33] and *CodeBlue*[34]) take an alternative approach and aim at developing individual miniaturized sensors connecting either to a body area network (BAN)[33] or hospital wide network[34]. In the case of *CodeBlue,* a healthcare sensor network is meant to increase medical efficiency and ease of care during emergency scenarios and standard hospital care by allowing caregivers to continuously monitor patient vital signs with computers and portable computing devices (smart phones, personal data assistants, tablet/personal computers, etc.)[34].

3.3 PSM for first responders and military applications

Development of first responder and military PSM equipment arguably faces greater challenges than either healthcare or fitness devices. First responder devices are required to have the same degree of accuracy and similar FDA approvals as hospital and home health care equipment while retaining the comfort and ease of use found with sports and fitness monitors.

Regardless of the wide variety of modern PSM devices within the three sectors, the design of systems for military, first responder, and industrial worker applications (e.g., Equivital, Hidalgo Ltd., Cambridge, UK; TrainTrak, Foster-Miller, Waltham, MA; BioHarness, Zephyr, Auckland, NZ) all combine a chest-mounted electronics sensor module attached to either a resistive band or textile shirt. This similarity in design can be attributed to the unique challenges faced by military PSM which necessitate a user friendly "wear and forget" device that does not require detailed technical knowledge to use, or involve multiple devices placed at various anatomical locations[35]. Devices similar to the thermometer pill (MiniMitter, Bend, OR) are useful for monitoring thermal strain but are not ideal for general use by soldiers or first responders as they are expensive and counter indicated by certain health conditions (e.g., esophageal stricture, gastrointestinal ulcers, and other uncommon gastrointestinal pathologies).

The extremes of physical activity which dismounted soldiers engage in further constrains the design of military PSM as sweating, motion artifact, and the obtrusiveness of any worn objects is much greater than generally encountered within a clinical setting. Soldiers are expected to perform in extremes of terrestrial climate and environment[36]. Similarly, PSM systems must weather arctic, tropical, and desert conditions without hampering range of movement or ability to perform tasks and still provide clinical grade physiological data.

4. TECHNOLOGIES – HEALTH STATE ALGORITHMS

Directly determining health state from on body sensors is challenging for multiple reasons: (1) physical measurement of physiological parameters must be non-invasive and therefore through indirect means (e.g., ECG, HR, respiratory rate, SpO_2), (2) basal or baseline readings of a given physiological metric may vary between individuals (e.g., resting heart rate may change as an individual's fitness increases or decreases, as an individual ages, or depending on emotional state), and (3) critical physiological functions may be strongly defended by compensatory biological mechanisms (e.g., symptoms of shock or dehydration may only be measurable at a point when an individual is already too injured for medical intervention to be effective)[37,38].

Figure 3a. The Warfighter Physiological Status Monitoring Initial Capacity system components: (1) Fluid Intake Monitor, (2) Vital Sign Detection System, (3) CPU, (4) Thermometer Pill for measuring core body temperature (Tcore), (5) Activity/actigraphy watch.

The 2006 Warfighter Physiological Status Monitoring Initial Capability WPSM-IC[40] is an effort by the U.S. attempted to address these problems from a system level. A combination of physiological and environmental sensors and physiology and physics-based heat transfer models were used to attempt to estimate life sign and multiple health states (e.g., thermal, hydration, cognitive). Figure 3a shows the sensor components, and 3b, the dependencies of the health state algorithms that allowed the system to calculate relevant health states in real time.

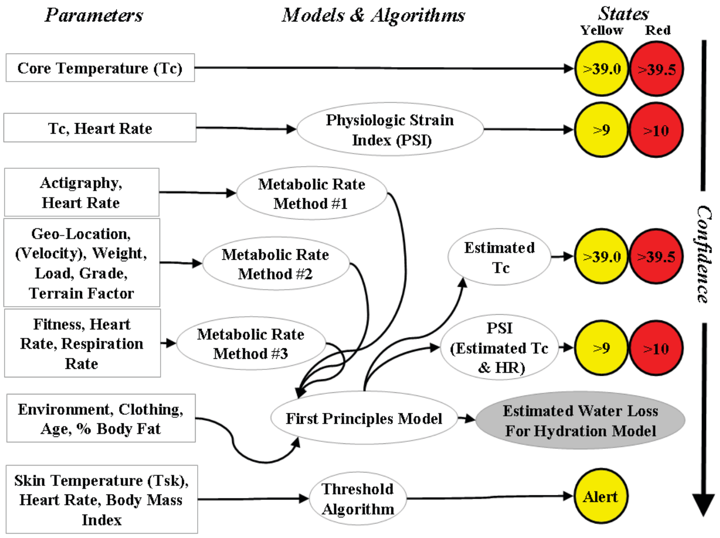

Figure 3b. A cascade of sensors and algorithms that enables the estimation of thermal state from input parameters, models, and state mappings. Graphic taken from Tatbul et al. 2004[41]. Note: The physiological strain index indicates heat strain based on HR and either core body temperature (Tcore/Tc) or rectal temperature[39].

More recent work has focused on developing non-invasive surrogates of critical health state measures such as core body temperature. Human core body temperature (Tcore) is a key measure of heat strain, and finding an acceptable non-invasive measurement method has been the focus of much research. Two prior efforts include estimating Tcore from specialized heat flow sensors placed against the head[42]; and an adaption of physics based heat transfer models[43] for use in real time[44]. While both these approaches are able to provide real time estimations of core body temperature, variability among individuals is too large for effective use in protecting during activities that place a group at high risk for heat illness or injury. Additionally, both methods are quite complex, one requires proprietary sensors located inside of a specialized helmet, while the other requires diverse measurements which may be hard to obtain. An alternate approach to deriving Tcore from sensors and physics, or from heat transfer models, is to estimate body heat from an already measurable physiological parameter. In this respect HR appeared to be a "noisy" measurement of the change in Tcore due to heat production and cooling. By using data with both HR and Tcore to learn a common filter model (see figure 4), we were able to infer Tcore from HR alone[45].

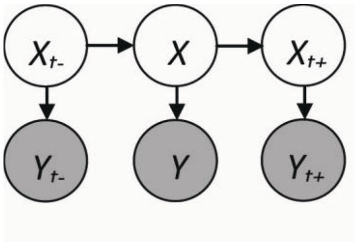

Figure 4. The Linear Dynamical System used to develop our Tcore estimation model. X represents the hidden state variable Tcore and Y represents the observed variable HR.

This method produced superior Tcore estimation results compared to current state-of-the-art techniques. For example, Tcore was estimated with an overall root mean square error (RMSE) of 0.30 ± 0.13 °C versus the modified heat transfer model RMSE of 0.35 ± 0.32 °C[43]. Over 85% of all estimates were within 0.5 °C of the true Tcore versus 82% from the specialized heat flow sensor placed against the head[42]. Despite the general success of this approach, it does not fill the need for Tcore estimation in every case as it demonstrated poor results for some subjects and did not accurately track periods of rapid cooling or heating.

The success of this computational physiology approach suggests that representing the underlying physiology in terms of observed non-invasive variables and unobserved internal state variables provides a framework to apply many current state-of-the-art state estimation algorithms. In the case of non-invasive physiological monitoring these representations would form the basis of Dynamic Bayesian Networks (DBN). Algorithms exist to learn the underlying DBN models from experimental data[46]. Previous work by Aleks et al. (2008)[47] describes successful use of a Bayesian network approach to improve ICU patient monitoring by modeling both the physiology and measurement equipment. A similar approach, but minimally validated, was also described by Borsotto et al. (2004)[48]. Figure 5 shows how a DBN could be improved for the accurate estimation of internal temperature.

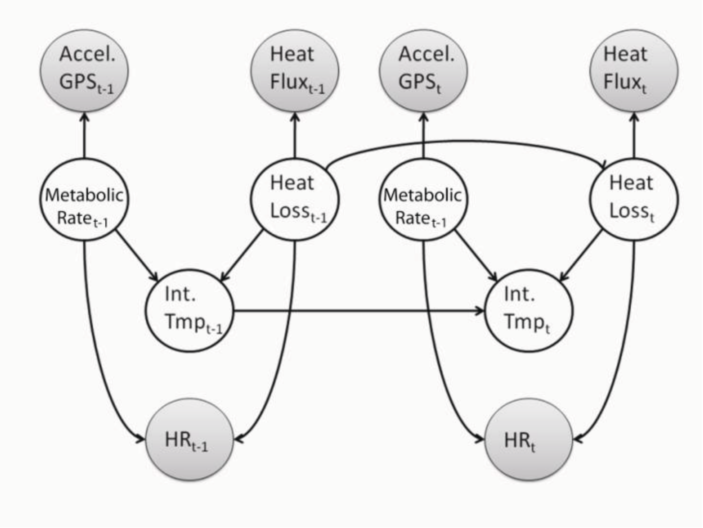

Figure 5: Dynamic Bayesian Network representation of the internal temperature problem, gray shaded nodes represent observed random variables, and white nodes represent unobserved internal states. Arrows show probabilistic dependence. Note: “Int. tmp” refers to core body temperature and “Accel GPS” refers to accelerometer global position system data.

Once the underlying DBN has been learned from experimental measurements of internal temperature, other unobserved nodes can be inferred from the model by computing the posterior probability distribution. Thus for the model in figure 5, we wish to find the probability of a test internal temperature (IntTmp = it) at the current time (t), all the current observations (Y = y), and the previous internal temperature ($IntTmp_{t-1} = it_{t-1}$) and previous heat loss ($HeatLoss_{t-1} = hl_{t-1}$):

$$P(IntTmp_t = it_t \mid Y = y, IntTmp_{t-1} = it_{t-1}, HeatLoss_{t-1} = hl_{t-1})$$

This DBN methodology provides an approach by which a hard to assess health state (thermal) can be inferred from a number of non-invasive sensors readings. This type of model may be applicable to other health state estimation needs such as hydration state or metabolic state.

5. STRATEGIES

With sensors and real time health state algorithms it is now possible to provide information to small group leaders about the health state of his/her team members. Acting upon health state alert information may prevent casualties and preserve team integrity.

Recently the Marine Corps, recognizing the need to reduce heat strain, allowed field commanders to reduce the level or modify the use of body armor (MARADMIN 0415/09). This doctrine, in conjunction with current work rest schedules and physiological monitoring, could form the basis of a feedback loop that allows for more efficient completion of mission objectives. Figure 6 shows an illustration of a commander's feedback loop.

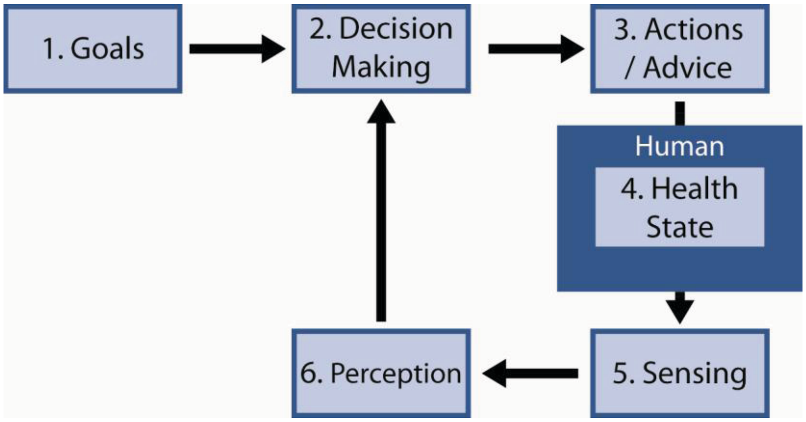

Figure 6. Team Management "Control" Loop

In order for this feedback loop to function effectively, not only must health state be accurately estimated but clear policies need to be in place, i.e. given the current health state and the overall goals what actions should a team member take next? Health state estimation is being addressed through the use of Bayesian techniques. Algorithms for optimal policy estimation have been developed by Kaelbling, Littman, and Cassandra (1998)[49], where policy estimation is represented in terms of a Partially Observable Markov Decision Process (POMDP). Their algorithm addresses the problem of picking a series of steps that optimizes reward once a final goal is reached. Our health state problem is very similar to this in that we wish to reach a goal while minimizing the detriment to health. More recently, Touissant (2008)[50] has demonstrated how to construct and solve a POMDP based upon a DBN model.

6. CONCLUSIONS

Military and first responders have previously relied on "buddy" systems or "eyes-on" medical personnel with visual access to patients. These approaches may be unreliable if untrained personnel are unable to recognize signs of dehydration, overheating, precursors to serious cognitive and metabolic failures, or other indicators of deteriorating health. Hostile settings, including military operations and extreme environments (high altitude, hot humid weather, etc.), may further reduce the ability of military or first responder personnel to identify and diagnose health state. Encapsulating protective equipment (body armor, CBRN suits) and remote settings can prevent effective eyes on assessment and limit the number and type of personnel available for diagnosis.

Ambulatory physiological status monitoring sensor systems have now reached the point where devices are available from a number of manufacturers; they can be worn comfortably for multiple days, and accurately measure some physiological variables in the presence of extreme military conditions. Some devices have even been certified by the Food and Drug Administration as equivalent to clinical heart and respiration rate monitors (e.g., Equivital, Hidalgo Ltd. Cambridge UK). These sensors are beginning to provide rich physiological data sets from extreme field settings (e.g., Iraq and Afghanistan). These data sets can provide the basis for researching health state estimation problems as an interdisciplinary effort between the machine learning and physiology communities. By solving the health state estimation problem through *computational physiology* and using an existing statistical POMDP framework, good advice about the management of team health in an extreme setting can be provided.

REFERENCES

[1] FM 3-0 Operations. Department of the Army field manual, Washington, DC; Headquarters, Department of the Army, 27 February (2008). Available online at: http://www.army.mil/fm3-0/fm3-0.pdf

[2] Afghanistan (2010). The World Factbook [online]. Acessed March 23, 2010, from U.S. Central Intelligence Agency: https://www.cia.gov/library/publications/the-world-factbook/geos/af.html

[3] Afghanistan (2010). The National Climatic Data Center National, Oceanic and Atmospheric Administration. Accessed March 23, 2010 from the U.S. Department of Commerce: http://www.ncdc.noaa.gov/oa/climate/afghan/data/surfaceafghanistan.html

[4] Dean, C.E., "The Modern Warrior's Combat Load, Dismounted Operations in Afghanistan," U.S. Army Center for Army Lessons Learns, US Army Research Development and Engineering Command, Natick Soldier Center, Natick (2004).

[5] TB MED 507, "Heat Stress Control and Heat Casualty Management," Department of the Army and Air Force technical bulletin, TBMED507/AFPAM 48-152(1), Washington DC. Headquarters Department of the Army. 7 March (2003). Available online at: http://www.usariem.army.mil/pages/download/tbmed507.pdf

[6] Yaglou, C.P., and Minard, D., "Prevention of Heat Casualties at Marine Corps Training Centers," Technical Report: AD0099920. Harvard School of Public Health, Boston, MA (1956).

[7] Yaglou, C.P., and Minard D., "Control of heat casualties at military training centers," A.M.A. Arch. Indust. H. 16, 302 (1957).

[8] Minard, D., Belding, H.S., and Kingston, J.R., "Prevention of heat casualties," J.A.M.A. 165, 1813 (1957).

[9] Minard, D., "Prevention of heat casualties in Marine Corps Recruits," Military Medicine (April), 261-272 (1961).

[10] Kark, J.A., Burr, P.Q., Wenger, C.B., Gastaldo, E., and Gardner, J.W., "Exertional heat illness in Marine Corps recruit training," Aviat Space Environ Med. 67(4), 354-60 (1996).

[11] Harman, E.A., Frykman, P.N., Pandolf, C., and LaFiandra, M.E., "Physical performance benefits of off-loading the soldier," Proc. of the Army Science Conference, 2-5, Orlando, FL (2002).

[12] Hoyt, R.W., Buller, M.J., Dlaney, J.P., Stultz, D., Warren, K., Hamlet, M.P., Shantz, D., Matthew, W.T., Tharion, W.J., Smith, P., and Smith, B., "Warfighter physiological status monitoring (WPSM): energy balance and thermal status during a 10-day cold weather U.S. Marine Corps infantry officer course field exercise," USARIEM Technical Report T-02/02 (2001).

[13] Beidelman, B.A., Hoyt, R.W., Pearce, F.J., Sims, N.M., Ditzler, D.T., Ames, J., Speckman, K.L., Blanchard, L.A., Garcia, A., Colquitt, N., Gaffney, W.P., and Freund, B., "User acceptability of design concepts for a life sign detection system," USARIEM Technical Report T04-02 (2003).

[14] McLean, J.A. and Tobin, G., [Animal and Human Calorimetry], Cambridge University Press, New York, 83 (1987).

[15] Moukabary, T., "Williem Einthoven (1860-1927): Father of electrocardiography," Cardiology Journal 14(3), 316-317 (2007).

[16] Zywietz, C., "A Brief History of Electrocardiography – Progress through Technology," Biosignal Institute for Biosignal Processing and Systems Research, Hannover, Germany (2003).

[17]McCullom, Burton, and Peters, Orville, S., "A New Electric Telemeter," Technology Papers, National Bureau of Standards No. 247, Vol. 17, January 4 (1924).

[18]Walter, P.L., "The History of the Accelerometer: 1920s-1996—Prologue and Epilogue, 2006," Sound & Vibration 41(11), 84-90 (2007).

[19] Satava, R., Angood, P.B., Harnett, B., Macedonia, C., Merrell, R., "The Physiological Cipher at Altitude: Telemedicine and Real-Time Monitoring of Climbers on Mount Everest," Telemedicine Journal and e-Health, 6(3), 303-313 (2000).

[20] Redin, S.M., "Marathon Man" Master Thesis, Department of Electrical Engineering and Computer Science, Media Laboratory, Massachusetts Institute of Technology (1998). Retrieved 02/02/2010. Available online at http://dspace.mit.edu/handle/1721.1/50057?show=full

[21] O'Brien C., Hoyt, R.W., Buller, M.J., Castellani, J.W., Young, A.J., "Telemetry pill measurement of core temperature in humans during active heating and cooling," Med. Sci. Sports. Exer. 30, 468-472 (1998).

[22] Hoyt, R.W., Buller, M.J., Redin, M.S., Poor, R.D., Oliver, S.R., Matthew, M.T., Latzka, W.A., Young, A.J., Redmond, D., Kearns, C., "Soldier Physiological Monitoring – Results of Dismounted Battlespace Battle Lab Concept Experimentation Program Field Study," Natick, MA. USARIEM Technical Report, T98-6, AD A332713 (1997).

[23] Chen, K.Y., "The Use of Portable Accelerometers in Predicting Activity Energy Expenditure," Presented at the Institute of Medicine, Committee on Metabolic Monitoring Technologies for Military Field Applications Workshop on Metabolic Monitoring Technologies for Military Field Applications, San Antonio, Texas, USA, Jan. 8-9 (2003).

[24] Chen, K.Y., Bassett, D R., "The Technology of Accelerometry-Based Activity Monitors: Current and Future," Med. Sci. Sports Exerc. 37(11 Suppl), S490-500 (2005).

[25] Bassett, D.R., Strath, S.J., "Use of pedometers to assess physical activity," In: Welk, G.J., ed., [Physical Activity Assessments for Health-Related Research], Human Kinetics, Champaign, IL, 163-177 (2002).

[26] Welk, G.J., "Use of accelerometry-based activity monitors to assess physical activity," in Welk, G.J., ed., [Physical Activity Assessments for Health-Related Research], Human Kinetics, Champaign, IL, 125-141 (2002).

[27] Hilbel, Thomas, Helms, T.M., Mikus, G., Katus, H.A., and Zugck, C., "Telemetry in the clinical setting," Herzschrittmachertherapie & Elektrophysiologie 19 (3), 146–64 (2008).

[28] Grossman, P., "The LifeShirt: A Multi-Function Ambulatory System Monitoring Health, Disease, and Medical Intervention in the Real World," Stud. Health Technol. Inform., 108, 133-141 (2004).

[29] Paradiso, R., Loriga, G., Taccini, N., Gemignani, A., Ghelarducci, B., "WEALTHY—a wearable healthcare system: new frontier on e-textile," J. Telecomm. Inform. Tech., April, 105-113 (2005).

[30] Di Rienzo, M., Rizzo, F., Merrigi, P., Castiglioni, P., Mazzoleni, P., Ferrarin, M., Ferratini, M., "MagIC: a Textile System for Vital Signs Monitoring. Advancement in Design and Embedded Intelligence for Daily Life Applications," Conf. Proc. IEEE Med. Biol. Soc. 2007, 3958-61 (2007).

[31] Pandian, P.S., Mohanavelu, K., Safeer, K.P., Kotresh, T.M., Shakunthala, D.T., Gopal, P., Padaki, V.C., "Smart Vest: Wearable multi-parameter remote physiological monitoring system," Med. Eng. & Physics 30, 466-477 (2008).

[32] Lurpano, J., Sola, J., Dasen, S., Koller, J.M., Chetelat, O., "Combination of Body Sensor Networks and On-Body Signal Processing Algorithms: the practical case of MyHeart Project," Proc. Int. Workshop on Wearable and Implantable Body Sensor Networks, BSN'06 (2006).

[33] Penders, J., Gyselinckx, B., Vullers, R., Rousseaux, O., Berekovic, M., De Nil, M., Van Hoof, C., Ryckaert, J., Yazicioglu, R.F., Fiorini, P., Leonov, V., "HUMAN++: Emerging Technology for Body Area Networks." In IFIP International Federation for Information Processing, Volume 249, VLSI-SoC: Research Trends in VLSI and Systems on Chip, eds. De Micheli, G., Mir, S., Reis, R., (Boston: Springer), pp. 377-397 (2007).

[34] Schnayder, V., Chen, B., Lorincz, K., Fulford-Jones, T.R.F., Welsh, M., "Sensor Networks for Medical Care," Technical Report TR-08-05, Division of Engineering and Applied Sciences, Harvard University, (2005). http://www.eecs.harvard.edu/~mdw/proj/codeblue.

[35] Anliker, U., Ward, J.A., Lukowicz, P., Troster, G., Dolveck, F., Baer, M., Keita, F., Schenker, e., Catarsi, F., Coluccini, L., Belardinelli, A., Shklarski, D., Alon, M., Hirt, E., Schmid, R., Vuskovic, M., "AMON: A Wearable and Multiparameter Medical Monitoring and Alert System," IEEE Trans. Inform. Technol. Biomed., 8(4), 415-427 (2004).

[36] Sawka, M.N., and Pandolf, K.B., "Physical Exercise in Hot Climates: Physiology, Performance, and Biomedical Issues," In: Pandolf, K.B., Burr, R.E., (Eds.) [Textbooks of Military medicine, Vol. 1. US Army Research Institute of Environment Medicine, Natick, MA, Chapter 3, 3-49 (2002). Available at: http://www.nap.edu/catalog.php?record_id=10981

[37] Convertino, V.A., Buller, M.J., Van Albert, S., and Freund, B.J., "Physiological Monitoring Combat Casualty Care," Chapter 3-6 in RTO-TR-HFM-132 "Real-Time Physiological and Psycho-Physiological Status Monitoring," Nato Research and Technology Organization Report, 77-86, March (2010). Available at: http://www.rta.nato.int/Pubs/RDP.asp?RDP=RTO-TR-HFM-132

[38] Committee on Metabolic Monitoring for Military Field Applications, "Rationale for Military interest and Current Capabilities in Monitoring Metabolism," In [National Academies of Science, Monitoring Metabolic Status – Predicting Decrements in Physiology and Cognitive Performance] The National Academies Press, Washington, D.C., Chapter 1, 15-36 (2004).

[39] Moran, D.S., Shitzer, A, and Pandolf, K.B., "A physiological strain index to evaluate heat stress," Am. J. Physiolo. Regul. Integr. Comp. Physiol. 275, 129-34 (1998).

[40] Tharion, W.J., Buller, M.J., Karis, A.J., and Mullen, S.P., "Accountability of a wearable vital signs detection system, " Proc. of the Human Factors and Ergonomics Society 51st Annual Meeting, Santa Monica, CA, Vol. 51, 1006-1010 (2007).

[41] Tatbul, N., Buller, M.J., Hoyt, R.W., Mullen, S.P., and Zdonik, S., "Confidence-based data management for personal area sensor networks," Proc. of the First Workshop on Data Management of Sensors Networks (DMSN). Toronto, Canada, Aug. (2004). Retrieved 03/02/2010. Available at: http://db.cs.pitt.edu/dmsn04/

[42] Gunga, H.C., Sandsund, M., Reinertsen, R.E., Sattler, F., and Koch, J., "A non-invasive device to continuously determine heat strain humans," J. Thermal Biol., 33, 297-307 (2008).

[43] Kraning, K.K., Gonzalez, R.R., "A mechanistic computer simulation of human work in heat that accounts for physical and physiological effects of clothing, aerobic fitness, and progressive dehydration," J. Thermal Biol., 22, 331-342 (1997).

[44] Yokota, M., Berglund, L., Cheuvront, S., Santee, W., Latzka, W., Montain, S., Kolka, M., and Moran, D., "Thermoregulatory model to predict physiological status from ambient environment and heart rate," Computers in Biology and Medicine, 38, 1187-1193 (2008).

[45] Buller, M.J., Tharion, W.J., Hoyt, R.W., and Jenkins, O.C., "Estimation of Human Internal Temperature from Wearable Physiological Sensors," IAAI (2010).

[46] Murphey, K.P, "Dynamic Bayesian Networks: Representation, Inference, and Learning," PhD. Thesis, University of California, Berkley (2002).

[47] Aleks, N., Russell, S., Madden, M.G., Morabito, D., Staudenmayer, K., Cohen, M., and Manley, G., "Probabilistic detection of short events with application to critical care monitoring," NIPS (2008).

[48] Borsotta, M., Sayell, C.T., Reifman, J., Hoyt, R.W., Nunns, G., and Crick, C.J., "Life-Signs Determination Model for Warfighter Physiological Status Monitoring," NATO Technical Report: RTO-MP-HFM-109, (2004).

[49] Kaelbling, L.P., Littman, M.L., and Cassandra, A.R., "Planning and Acting in partially observable stochastic domains," Artificial Intelligence, Vol. 101, 99-134 (1998).

[50] Toussaint, M., "Probabilistic inference as a model of planned behavior," Kunstliche Intelligenz, Vol. 3 (2009).