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Remote Physiological Health and Status Monitoring of First Responders: Promises, Practicalities, and Prospects

February 2015

TF Sanquist

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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Summary

Key concepts to consider for the First Responder of the Future include the ability to remotely monitor various physiological and health parameters by means of wearable sensors and local area communication of data to incident command. This report reviews the rationale underlying Remote Physiological Monitoring of First Responders (RPMFR) to both 1) provide a basis for further research and development investments in technology by the U.S. Department of Homeland Security (DHS) and 2) guide technology demonstrations and evaluations. The focus is primarily on firefighters, due to the high physical workload demands, but the results are applicable more generally to law enforcement officers, medical workers, and others. The report addresses operational concepts for RPMFR as described in recent literature to enable discussions of operational demands on first responder personnel. Specific areas covered include cardio-respiratory system demands, heat stress and dehydration, human performance impacts of operational demands, the state of wearable technology for remote physiological monitoring, issues associated with the meaning and interpretation of remote physiological signals, and integrative concepts from the study of mental and physical fatigue (including self-monitoring and peer observation) as they pertain to developing practical applications to improve first responder safety.

Based on the research discussed within this report, the following conclusions are drawn regarding remote physiological monitoring for first responders:

- Remote monitoring and transmission of cardiac parameters for first responders is feasible and accurately reflects the physical demands of the job.
- Remotely monitoring heat stress is *possible* but not operationally practical.
- Remotely monitoring dehydration is not currently feasible on the basis of existing sensor capability.
- Software algorithms and outcome measures for physiological signals are relatively immature and require support from clinical experts.
- Near- or supra-maximal heart rate, increased core temperature, and dehydration are routinely encountered in firefighting operations.
- Operational personnel are generally aware of levels of exertion, heat stress, and dehydration when measured by self-report.
- The physiological impacts of operational demands can impair worker cognitive functioning.
- Awareness-based models of physiological and cognitive performance impacts can be taught and can influence subsequent activity.

The ability to record and transmit physiological variables from first responders has been available for a considerable period of time but has yet to be incorporated as a routine aspect of turnout gear and post-operation analysis or used for fitness and health guidance for first responders. The reasons for the current lack of systematic use of RPMFR are multiple, some of which are technical, such as sensor size, weight, battery life, etc. However, these problems are rapidly diminishing, and at least one system has been used multiple times in live fire operations and continues to be employed in other venues such as sports training. More problematic is the lack of clearly defined user needs, system concepts, and outcome measures that can be effectively employed to improve worker safety and health. Although various national standards organizations such as the National Fire Protection Association (NFPA) recommend

health screening and lifestyle adaptations to address cardiovascular risk, adopting such approaches remains voluntary and costly. As a result, a cycle of individual project-based demonstrations occurs periodically, but does not lead to sustained system refinement based on prior research findings.

For remote physiological monitoring to become a useful and routine part of everyday first responder operations, the following programmatic research steps are recommended, based on a stakeholder process model for wearable sensors in the marketplace:

- Articulate the specific need for RPMFR
- Develop Operations Concepts
- Design programs and teams of experts to conduct research
- Screen and select technologies
- Collect operational data
- Develop analytics
- Develop feedback and training
- Evaluate impact
- Embed research results and materials within a credible dissemination pathway for broader application

Each of these points is discussed within this report, followed by strategy recommendations for implementation.

Author Information

Thomas F. Sanquist is a staff scientist in the National Security Directorate of the Pacific Northwest National laboratory. He is trained as a cognitive neuroscientist, having received a PhD and Master of Arts from the University of California, Los Angeles, and a Bachelor of Arts in experimental psychology from the University of Michigan. His work focuses on human-systems integration, human factors engineering, and worker safety and security. He can be contacted at Sanquist@pnnl.gov.

Acronyms and Abbreviations

CONOPS	Operations Concepts
CPAT	Candidate Physical Ability Tests
DHS	Department of Homeland Security
DOD	Department of Defense
ECG	electrocardiogram
FDA	U.S. Federal Drug Administration
IAB	Interagency Board
NFPA	National Fire Protection Association
PNNL	Pacific Northwest National Laboratory
PPE	personal protective equipment
R&D	research and development
RPMFR	Remote Physiological Monitoring of First Responders
RTA	Responder Technology Alliance
WPSM	Warfighter Physiological Status Monitoring

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1.0 Introduction and Background

The 2012 research and development (R&D) priority list of the Interagency Board (IAB)[1] includes Body-Worn Integrated Electronics as a high priority item. The priority description is for

> "a body-worn electronics system integrating enhanced communications capabilities, locations and tracking capabilities, situational awareness and environmental sensing capabilities, physiological status monitoring capabilities, and respiratory protective equipment status."

Such systems would be valuable in the overall enhancement of situational awareness for incident commanders and responders (location, impacts of operational demands on personnel) and monitoring and feedback of individual physiological signals for responders. This report reviews research work in the following areas:

- Cardiovascular strain in firefighting operations
- Heat stress
- Dehydration
- Wearable sensors
- Signal processing and algorithm development
- Integrative theories of fatigue and performance
- Self-assessment and behavioral observation

The findings are integrated to make recommendations to support the DHS First Responder Technology Alliance (RTA) goals of near-term R&D, operational demonstrations and evaluations, and targeted technology investments. The RTA was established to accelerate the development of solutions to first responder needs and requirements by identifying, analyzing, and recommending solutions that improve responder safety, enhance their ability to save lives, and minimize property loss.

A number of operational, social, and technological elements have converged in recent years to lend credence to the concept of operational physiological monitoring for first responders. Operational factors include the need for working in enclosed, physically demanding circumstances for sustained periods, often without clear location cues or communications – as in responses to catastrophic events. Socially, the increased emphasis on preparation for emergency responses to terrorism or extreme weather events focused attention on the capacities of the first responder community to surge and sustain operations in circumstances that may be outside the general training basis for response preparedness. Technologically, there has been an evolution in the development of lower-cost physiological sensors that can be integrated

[1] The IAB was co-founded in 1998 by the Department of Defense (DOD) and Department of Justice to improve the safety of responders through development of an effective, integrated response system. IAB stakeholders represent local responders and federal agency partners (IAB charter, 2010; https://iab.gov/Uploads/FINAL_ADOPTED_IAB_CHARTER_03_10_10.pdf).

into wearable form and provide local area wireless transmission. Together, these factors point toward eventual operations concepts that involve moment-to-moment assessment of physiological health and status of first responders. The most immediately applicable circumstances for these applications would be firefighting operations, but they extend to other responders as well – for example law enforcement personnel engaged in search and rescue or sustained crowd control operations[2].

Considerable impetus for remote physiological monitoring for first responders (RPMFR) comes from developments within the Warfighter Physiological Status Monitoring program (WPSM) (Friedl, 2004). More than half a century of physiological monitoring research has been conducted by various military organizations, initially aimed at assessing aviator performance (Sem-Jacobsen, 1959) and radar operator vigilance (Beatty, et al., 1974). These early studies relied on the relatively controlled environment of cockpit and radar simulators where personnel can be easily connected to bulky recording and analysis equipment. While the early NASA space flights employed remote monitoring of astronauts, it was not until fairly recently that sensor and communications technologies evolved to the point of making operational remote monitoring feasible on a less-tethered and larger scale. Progressive refinements of ambulatory monitoring systems for electrocardiogram (ECG) (Holter, 1961), arterial blood pressure (Schneider, 1968), electroencephalogram (Ives and Woods, 1975), and sleep recording (Wilkinson, Herbert and Branton, 1973) evolved into miniaturized sensors to record a variety of parameters in freely moving people (Goodwin, 2012). The notion of ubiquitous computing (Weiser, 1991) entails technologies that "weave themselves into the fabric of everyday life until they are indistinguishable from it."

The WPSM program grew out of the long-established Military Operational Medicine Research Program in 1996. The goal of the program is to "make real-time performance predictions that leaders can use to assess the readiness status of their forces" (Freidl, 2004). The basic concept is that body-worn sensors, coupled with analysis, would yield a simple "green, yellow, red" indication – with red indicating that systems failed and the soldier is a casualty. Components of such a system are illustrated in Figure 1 (Apiletti, et al., 2009).

[2] The social and technological trends have been mirrored by similar developments in research disciplines related to remote physiological monitoring, and to fully assess the prospects for application requires evaluation of scientific literature from diverse domains, including exercise physiology, computer science, ergonomics, cognitive psychology, and neuroscience. This range of disciplinary review is necessary to fully articulate what is reasonably achievable with remote physiological monitoring in operational settings and to distinguish scientific validity from technological imperative.

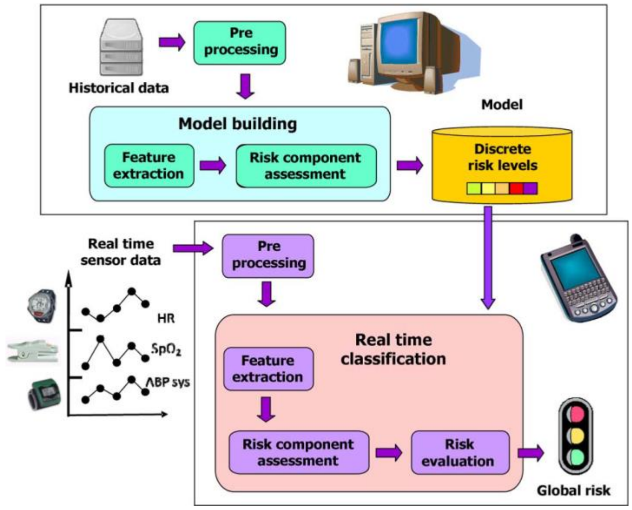


Figure 1. Components of a real-time physiological alerting system. (Apiletti, et al., 2009)

The systems are intended to learn over time and address the range of individual responses encountered in operational environments, which would exceed those that can be ethically established in a laboratory setting. Friedl (2004) points out that while sensing and communications technologies are vastly improved, most current research studies simply examine the same factors and relationships that have been explored for 50 years or more. Technological advantages of miniaturization and wireless communications expand the range of possibilities, but many available systems seem to represent simple telemetric applications of clinical or sports physiology monitoring systems. This type of technology-driven research tends to limit applications and does not focus attention where it is most needed – defining suitable outcome measures. Such measures are important so that lab-based research and medical reference values can be translated into operationally relevant outcomes. The desired end result of R&D in this area is a well-defined set of outcome measures linked to meaningful alterations in responder performance, health, and status. End-use scenarios would entail screening prior to deployment, monitoring and potential intervention by command personnel, individual responder feedback for activity modification, and general fitness-for-duty assessment during shift rotations.

The prospect for practical application of remote physiological monitoring is shown by a study of cardiac event alerting in an emergency department waiting area. Occasionally, patients in these areas deteriorate while awaiting care, although they do not initially meet the criteria for immediate telemetric monitoring. Pollack (2009) reports an evaluation of wireless monitoring of patients who did not meet standard emergency department criteria for telemetric monitoring (chest pain, respiratory distress, unstable vital signs) but were seeking medical attention for a variety of other urgent complaints (gastrointestinal, injury, neurologic/psychiatric, respiratory, substance abuse, etc.). Using a NetGuard Automated Clinician Alert System in a total of 298 patients, there were 20 productive clinical alarms (6.7% of patients), the majority of whom (80%) were transferred from the waiting area to the treatment area in an expedited manner. There were 10 artifactual alarms in four patients (1.7%) that were readily discerned as such, due to factors such as movement, poor sensor adhesion, etc. While this is a small study, it shows that with a clearly defined set of measures (confirmed tachycardia or bradycardia) related to an outcome (i.e., more rapid treatment) remote physiological monitoring can provide a medically useful benefit.

2.0 Conceptual and Theoretical Considerations: Operational Demands and Responder Functional State

The underlying conceptual and theoretical basis for RPMFR involves a metabolic/energetic model of performance. These metabolic processes are the basis of responses that allow people to survive in adverse environmental circumstances, entailing for example, generalized sympathetic nervous system activation in demanding situations (National Research Council, 2004). The assumption is that alterations in measurable physical, physiological, or cognitive parameters may reflect the earliest indicators of change in health and status and measures of these parameters can be predictive markers of current status or impending failure. A key assumption in concepts for RPMFR is that responders may not be aware of reaching dangerous levels of overheating, dehydration, exertion, stress, fatigue, or sleep deprivation, because of various operational pressures. Alerts or warnings to incident commanders and individual responders would permit intervention and reduce potential casualties.

The "limited awareness" idea associated with monitoring systems gives less credence to worker perceptions of exertion and fatigue than they deserve. A substantial amount of research in the domains of exercise physiology, sleep and performance, and cognitive performance illustrates orderly relationships of task requirements with various types of self-rating scales (of exertion, perceived effort, alertness, etc.) (National Research Council, 2004). In sleep research, for example, physiological tests used to measure fatigue tend to be highly correlated with self-rating scales. It is suggested that a single measure of effort sense or mood state may be superior to physiological measures in various circumstances.

While not expressly stated in discussions of remote monitoring, there is an implicit model of capacity – muscular, cardiac, respiratory, mental – for which physiological measures will supposedly provide a gauge. A further assumption is that certain limits exist that are best measured with technical instrumentation. This theoretical orientation is based largely on models of physical fatigue in which local muscles become unresponsive due to metabolite build-up and maximum cardiac output is reached; this is the so-called "limitation" or "catastrophe" model of exercise physiology (Noakes, et al., 2005). Considerable evidence exists, however, to suggest that physical exertion is self-limiting not because of peripheral muscular fatigue or myocardial ischemia (i.e., loss of capacity to respond), but instead based on a *central governor* system in which sensory information from heart, brain, and respiratory muscles alert the brain to threats of ischemia in those organs (Figure 2, from Noakes, 2012). Multiple lines of evidence point to fatigue as a centrally mediated sensation that serves to reduce exercise intensity; hence, various paces can be maintained, and in some instances extreme "surges" of physical effort exhibited, without concomitant muscle or organ damage. These physical capacity models have analogous counterparts in theories of cognitive performance and fatigue (Hockey, 2013).

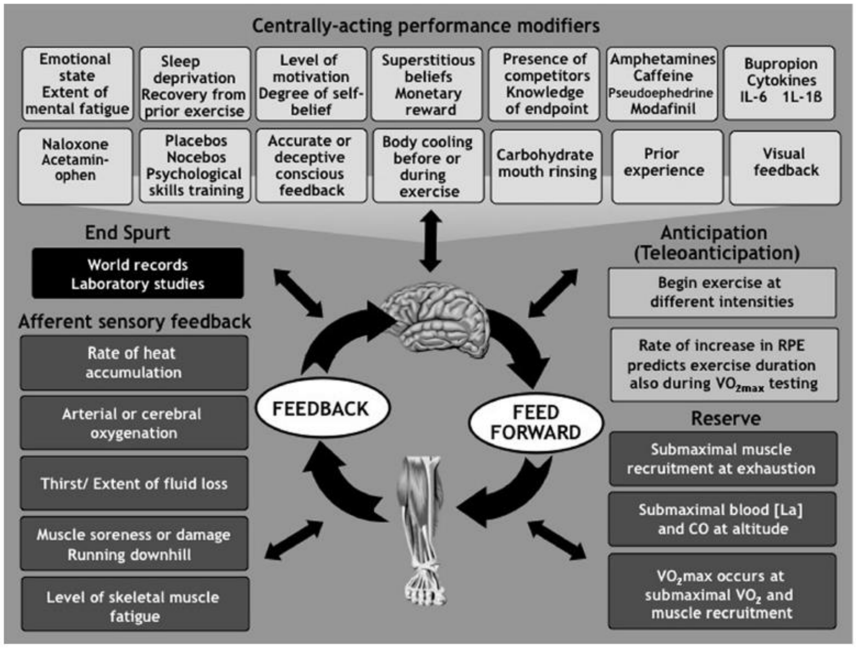


Figure 2. Central governor model. (Noakes, 2012)

The experience of fatigue and the perception of effort are paramount in current theories (Noakes, 2005; Hockey, 2013) and stress the importance of integrative research approaches. Hockey, for example, places considerable emphasis on the need for research that incorporates more realistic representations of work and fatigue, to include neuroscience measures (e.g., remote physiological monitoring) as well as rigorous assessment of subjective feelings through self-report measures. An example of this type of work is illustrated by Mehta and Parasuraman (2014), in which combined physical and cognitive tasks were evaluated with physiological, performance, and self-report measures; the experiment showed clear interactions between physical and mental effort in all measures.

From a practical standpoint, DHS RTA RPMFR research might aim to develop, test, and deploy wearable sensors as well as the decision rules for alerting and worker-oriented training based on these data. The latter can be used to enhance the ability of individual workers to recognize mismatches between current work pace and what they are able to sustain and strategies for adjustment based on operational conditions.

3.0 A Psychophysiological Model of First Responder Job Performance

The physiological changes experienced by first responders working in adverse operational conditions can be characterized by a model of worker fatigue, shown in Figure 3. The basic structure involves various *performance shaping factors* such as cardiovascular strain, psychological stress, thermal stress, and dehydration. These factors interact to influence the effectiveness of important aspects of job functioning. We focus here on *cognitive performance* for several reasons: (1) effective mental processing such as attention, perception, memory, etc., are key elements of assessing and responding to unfolding emergency events; (2) physiological responses influence emotional and cognitive processing and viceversa; (3) significant failures in responding to urgent events are often the result of cognitive lapses; and (4) research data, to be reviewed below, suggest that there are predictable declines in cognitive performance as a result of the types of exposures encountered by emergency first responders.

Figure 3 illustrates the interactions of psychological, physiological, and cognitive performance outcomes that can result from high-demand emergency response situations. It also suggests that there are potential countermeasures that can be developed that may help to mitigate some of these problems. Some potential countermeasures may seem straightforward, indeed simplistic, such as hydration to reduce impact of heat stress and dehydration. However, as data presented below illustrate, even the simplest measures (such as drinking enough water) are sometimes not practiced routinely.

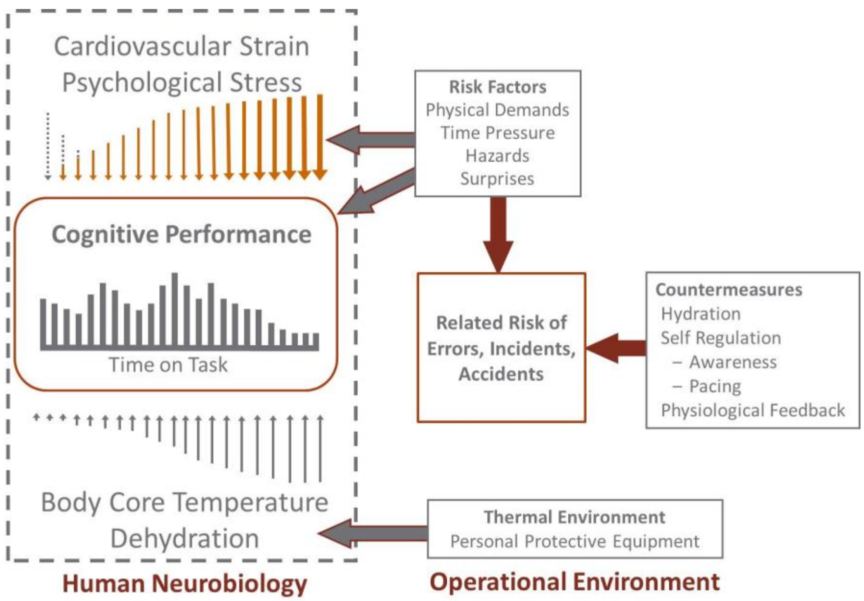


Figure 3. Psychophysiological model of job performance impact for emergency first responders.

In addition to physiological demands, emergency management places unique task and cognitive demands on the first responder. These include more general elements such as unanticipated events (surprise) and time pressure, as well as more specific requirements. Individual firefighters, for example, engage in a relatively continuous cycle of cognitive activity involving situation assessment, threat reduction, route planning and management, and extraction if necessary. While most research focuses on incident commanders, these activities are also performed by individual firefighters and they require basic cognitive processes such as attention and memory, which have been shown to be impaired by high stress situations (Fern, et al., 2008; McLennan, et al., 2014).

The implication of the psychophysiological model is that certain measures – such as remote monitoring – can be employed to characterize the response of first responders to conditions in the operational environment. By combining this information with established knowledge of performance impacts and approaches to self-regulation through awareness and pacing, the relative risk of accidents and injuries can be reduced. Similar psychophysiological models have been applied in the domain of worker fatigue across many operational settings and for augmenting cognitive performance in selected military applications. In the subsequent sections, we focus on the operational demands of firefighting, as the conditions tend to be the harshest, and address the specific impacts of cardiovascular strain, heat stress, and dehydration.

4.0 Operational Demands of Firefighting

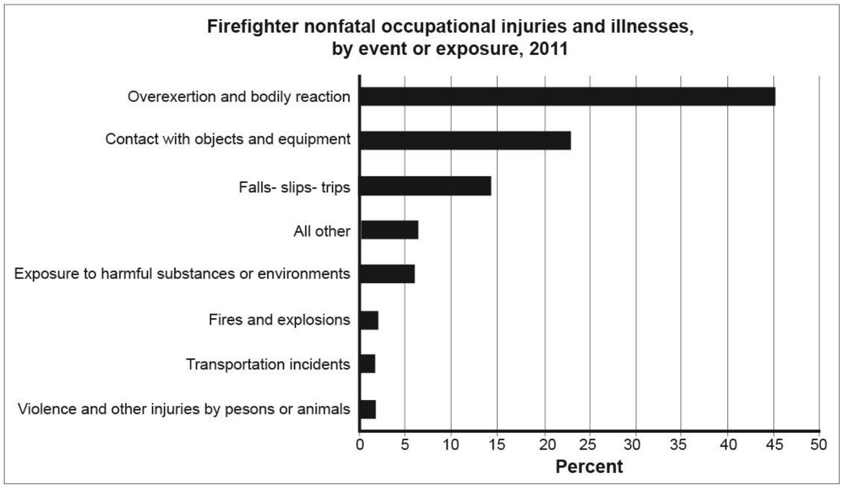
Firefighting is generally recognized as a hazardous occupation. The work is dangerous, physically strenuous, and involves prolonged exposure to heat with varying levels of personal protective equipment (PPE), dehydration, and psychological stress. The physiological function of humans under these stressful conditions entails adaptive responses of the cardiovascular system involving changes in heart rate, blood pressure and respiration, and the thermoregulatory system via changes in skin and core temperature, respiration, vasodilation, and sweating. The confluence of these various stressors can lead to physical and mental performance degradation, endangering individuals or teams of firefighters. The following three sections discuss operational demands in terms of cardiovascular strain, heat stress and performance, and dehydration and performance. Although the physiological responses to operational stressors are complex and interrelated, separate discussions are warranted to elucidate understanding of potential monitoring and mitigation approaches.

4.1 Cardiovascular Strain

Recent statistics for firefighter on-the-job injuries show that up to half of all such injuries occur as a result of overexertion and bodily reaction (Figure 4). In 2013, of the 97 on-the-job firefighter fatalities, 33% were classified as being due to overexertion (Fahy, LeBlanc and Molis, 2014). Longer term and comparative analyses by Soteriades, et al., (2011) suggest that nearly half of the on-duty deaths of firefighters may be due to cardiovascular disease, in contrast with police officers (22%), construction workers (12%), emergency medical services workers (11%), and all occupations combined (15%). Most of the firefighter deaths from cardiovascular disease occur during the most strenuous tasks, such as fire suppression. However, firefighter mortality from cardiovascular disease is similar to the general population, suggesting that underlying cardiovascular disease in combination with strenuous activity is the principal risk factor for on-duty death from cardiac arrest (Soteriades, et al., 2011).

It is unclear whether on-duty death from cardiac arrest is preventable on the basis of alerts provided to firefighters as they approach or exceed maximum heart rate (Brown and Stickford, 2008). Extreme physiological responses are routine in the firefighting job and may indeed be the pre-requisite of getting the job done. However, better knowledge of underlying cardiovascular disease, coupled with knowledge about individual levels of cardiovascular strain during job performance and appropriate interventions (awareness, self-monitoring, health improvement, exercise, re-assignment to lower risk activity) may help to reduce on-duty cardiac deaths.

From the standpoint of absolute numbers of non-fatal on-the-job injuries, physiological monitoring may provide a benefit. As shown in Figure 4 (Bureau of Labor Statistics, Firefighter Fact Sheet, 2011), approximately 45% of the non-fatal injuries experienced by firefighters are due to overexertion and bodily reaction. The exact nature of the overexertion is not clear from published reports, but we can surmise that in general such injuries are a result of a mismatch between operational demands, firefighter effort and their physical capability. This area may be amenable to self-monitoring, developed through a program of systematic behavioral observation with supporting data from physiological monitoring.



Source: U.S. Bureau of Labor Statistics.

Figure 4. Causes of injury for firefighters. (Bureau of Labor Statistics, Firefighter Fact Sheet, 2011)

The issue of strenuous occupational demands on firefighters in relation to health risk has been the subject of research for nearly 40 years. Early studies of firefighter physiological profiles (Lemon and Hermiston, 1977) evaluated functional capabilities of 45 professional firefighters and found that key variables such as maximum oxygen uptake, recovery oxygen uptake, and arm and leg strength all decreased linearly with age. Although the data were within the normal range for sedentary Americans, it suggested that higher levels of training and fitness would be appropriate due to the physical demands of the job.

The primary objective of research conducted over this long period was to better understand the magnitude of physical demands on firefighters, to better define fitness selection and readiness standards, to evaluate the impact of various protective clothing ensembles, and to support training simulations and entry table limits for operations. The following material focuses on the studies that are most illustrative of operational impacts on heart rate response. Material in this and subsequent sections draws from the comprehensive reviews of Guidotti (1992) and the United Kingdom Office of the Deputy Prime Minister (2005).

An early study of heart rate in response to live operations was conducted in 1975 by Barnard and Duncan. Their results from 35 firefighters responding to 189 alarms showed an initial rise in heart rate in response to the alarm, a decrease to levels above resting (but still elevated while in transit to the fire) and a subsequent rise to near- or supra-maximal levels during firefighting. Of particular note was the increase in heart rate in response to impending danger, such as potential roof collapse. Further, these investigators observed circumstances in which firefighters completed one call, only to be sent immediately to another. Under these circumstances heart rate was elevated to near maximal levels (180 beats-per-minute) for 90 minutes.

Manning and Griggs (1983) evaluated physiological responses during live firefighting exercises. The general pattern observed was that heart rate rapidly increases to 70-80% of maximum within the first minute of activity. As the fire progresses, heart rate is maintained at 80% to more than 100% of the maximum for the duration of operations. These levels were maintained even with the addition of protective equipment, suggesting that firefighters adapt their levels of exertion to remain constant after the initial increase.

Subsequently, numerous studies of firefighter physiological response were performed throughout the 1990s and the early 2000s. The principal objective of these studies was to provide empirical data to define more realistic training regimens and fitness standards and tests. A detailed review of these studies is available in the compilation by the United Kingdom Office of the Deputy Prime Minister (2005). The general findings of this research include:

- Cardiovascular strain increases with physical demands. Stair climbing and hauling equipment is found to be the most taxing activity in multiple studies.
- Firefighter rank ordering of physical demands is generally correlated with physiological responses.
- Firefighters self-select their work intensity, and it correlates with general fitness level.

Some uncertainty remains regarding the extent to which screening tests such as the Candidate Physical Ability Tests (CPAT) can simulate the range of physiological responses during live firefighting. Williams-Bell, et al. (2009) report similar responses in cardiac effects and oxygen uptake between firefighting simulations and CPAT testing, while Angerer, et al., (2008) reported a disparity between responses in medical screening and live-fire exercises – with live-fire exercises resulting in substantially higher physiological demands.

In contrast to most of the studies conducted in this area, which employ simulations or training exercises, Brown and Stickford (2008) utilized a field research approach to record physiological data during responses to actual fires in the Indianapolis Fire Department. In this study, a total of 88 working structure fires involving firefighting activities were studied, with data obtained from 56 individual workers. In addition to replicating earlier findings of high heart rates beginning with the alarm and continuing during the response and in some cases for several hours afterwards, Brown and Stickford reached several general conclusions based on detailed statistical analysis:

- Extreme cardiovascular strain (e.g., maximal heart rates and respiration) is routinely observed in firefighting tasks. These levels are maintained for as long as 25 minutes continuously.
- Overall fitness level, particularly in terms of body fat percentage, determines the extent to which maximal exertion levels, based on age-predicted norms, can be attained. In other words, those firefighters who are less fit are not able to work as hard in terms of cardiovascular strain measures.
- Recovery time following an incident may be a useful indicator of job-related fitness.
- Physiological monitoring, focused on a single parameter (such as heart rate) in order to provide a basis for removing the firefighter from the scene to prevent *potential* heart attacks, is likely to be counterproductive, since the high heart rates are demanded by the job requirements.

The Brown and Stickford study suggests, on the basis of a variety of data concerning cardiovascular disease risk factors, that screening and risk factor reduction (e.g., losing weight, improving fitness) should be a focus for reducing on-duty heart attacks. This could be facilitated and even personalized to the individual firefighter, with feedback provided by cardiac monitoring during operations and systematic self-monitoring of effort or related dimensions. This type of application is likely to require substantial R&D to develop, as shown by a recent study of remote advanced electrocardiography by Dolezal, et al.

(2014). Rather than using ECG obtained during training simulations or live fire operations, these investigators sought to demonstrate that resting remote ECG, administered by trained operational personnel and interpreted remotely by experts, could be used to identify underlying coronary artery disease. The study was successful in that it produced results equivalent with diagnostic results that would be obtained with more invasive tests and illustrated the need for expert application review to reach diagnostic conclusions. Thus, while the data were obtained in a short period of time by operational personnel in their local stations and transmitted remotely for interpretation, real-time decision making on cardiac parameters for firefighters will require substantially more development of algorithms, classification, and diagnostic validation.

4.2 Heat Stress and Cognitive Performance

Firefighters are regularly exposed to hot environments as a reoccurring part of the job. Various levels of PPE can be utilized to mitigate the impacts of heat stress to some extent, but firefighters may be exposed to temperatures as high as 356°F for at least several minutes (United Kingdom Office of the Deputy Prime Minister, 2005, Table 2). Little data exist concerning temperatures experienced in operational firefighting; instead, knowledge is derived from measures taken during training exercises with live fire suppression using sensors on the firefighter (Foster and Roberts, 1994; NIST/FEMA, 2008). Based on these data, it can be expected that firefighters will encounter environmental temperatures ranging from 104°F to 248°F, with occasional extremes above these levels. The NIST studies also reported environmental temperatures associated with total room involvement (Class III) up to 482°F and flash-over or backdraft (Class IV) up to 1500°F. Flammable liquid and chemical fires can produce environmental temperatures up to 2000°F (FEMA, 2008). Specific time limits for exposure do not seem to have been established, probably because it is difficult to know exactly what type of conditions will be encountered until they are observed. Further, it has been shown that under controlled conditions, the same size and type of fire will yield variable temperatures (Office of the Deputy Prime Minister, 2005).

The principal physiological impact of heat exposure is the potential rise in core body temperature. This can be associated with escalating levels of health effects and performance impacts ranging from the relatively minor, such as heat rash, to life threatening, such as heat stroke. Numerous studies have measured body temperatures achieved by firefighters during training exercises (e.g., Smith, et al., 1997; Baker, et al., 2000). These studies used diverse measurement methods, including gastrointestinal pill, aural and rectal probes, and observed temperatures up to 104°F. Although there appears to be no set standard or safety limit for body temperature achieved during firefighting, the United Kingdom group suggests an upper limit of 102.2°F for training exercises. Smith, et al., (1997) note that correlations between aural temperature and thermal sensations were moderately high (0.71 to 0.81), suggesting that firefighters had a "perceptual window into actual physiological response." Figure 5 (United Kingdom, 2005) illustrates the steady rise in core temperature (Celsius scale) during a firefighting simulation. Recent work by Horn et al. (2013) also shows that core temperature increases continue for as long as 3 hours, even with rest breaks.

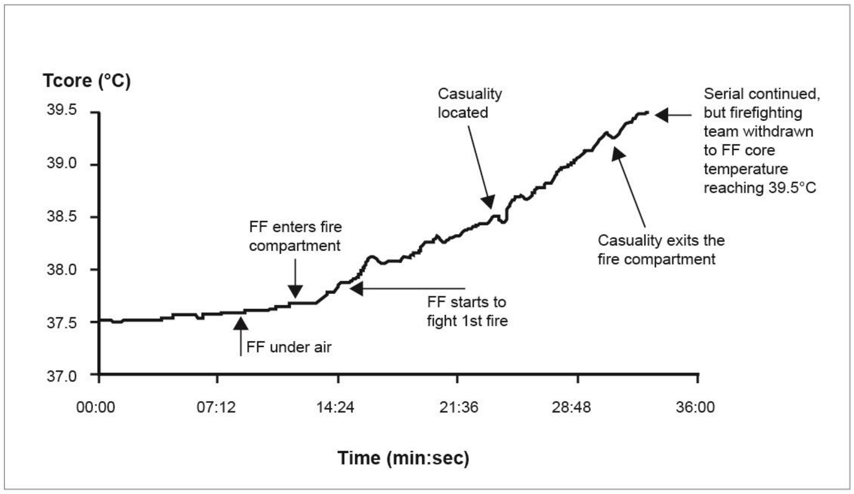


Figure 5. Rise in core temperature during firefighting. (United Kingdom, 2005)

There is very little data concerning the effects of heat stress on firefighter cognitive performance. Anecdotal data and observations suggest that mental processing is impaired during prolonged exposure; however, it is difficult to objectively demonstrate this. The United Kingdom Office of the Deputy Prime Minister (2004) tested firefighters on tasks of spatial memory, choice reaction time, and visual information processing after a firefighting simulation, but no changes were observed – possibly because 30 minutes had elapsed since the exercise ended.

The signs and symptoms of heat exhaustion, as distinct from the life-threatening circumstances of heat stroke, include effects on consciousness, such as giddiness, vertigo, and potential loss of consciousness by fainting (OSHA, 1999). These symptoms are similar to the effects of fever, which can affect the ability to concentrate. This suggests that prolonged exposure to heat, in addition to simply raising core temperature, will have detrimental impacts on firefighter cognitive functioning.

Hancock and Vasmatzidis (2003) reviewed the state of knowledge regarding cognitive effects of heat stress; nearly all of this work is conducted in laboratory settings using controlled tests of mental performance. While it is difficult to generalize from this type of work to the field settings encountered by firefighters in operational conditions, the laboratory cognitive tests can be considered abstractions of the fundamental processes involved in the mental performance of firefighters. Thus, impairments observed in laboratory situations are likely to represent similar alterations of cognition resulting from heat exposure in the field.

The effects of heat stress on cognitive tasks have been studied with a wide range of performance tests, from simple reaction time (pressing a key as fast as possible in response to a signal) to much more complex tasks such as simultaneous perceptual-motor tracking and rare event detection. Consequently, there are conflicting findings regarding the effects of heat stress, including degradation, enhancement, or some combination of both over time. When the studies are classified and meta-analyzed in terms of task type (simple or complex), thermal exposure, and exposure time, a resulting pattern suggests potential heat stress limits. Figure 6 (Hancock and Vasmatzidis, 2003) illustrates this relationship for a variety of tasks and predicted levels of core temperature based on environmental temperature, exposure time, and predicted core temperature increases.

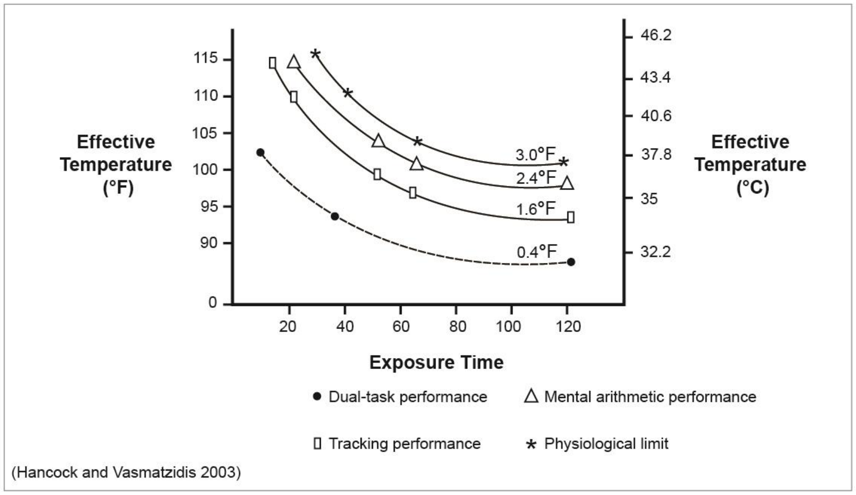


Figure 6. Anticipated heat stress impacts for various cognitive tasks. (Hancock & Vasmatzidis, 2003)

The upper curve on Figure 6 represents a potential physiological limit. It can be seen that progressively more complex tasks (dual task being the most complex) show impairment at lower temperatures and exposure times. This suggests that there is progressive cognitive impairment as operations in the heat are extended, and this may provide a basis for monitoring and self-assessment. Based on the data described above about the high core temperatures achieved by firefighters during training, it is reasonable to conclude that some level of impact on cognitive function occurs.

4.3 Dehydration and Performance

The heat exposure, physical exertion. and PPE ensembles involved in firefighting can lead to dehydration, which can exacerbate the other cardiovascular and thermoregulatory problems discussed above. Water is the main component of the human body, comprising 50-70% of body mass (Kenefick, et al., 2012). Dehydration occurs when water or other fluid intake does not keep up with fluid loss. There are individual differences in total body water composition, with leaner individuals having a much higher percentage of water than those with higher fat body mass. While thirst and hunger sensations generally regulate intake to offset water loss, there are considerable individual differences in water needs across individuals and levels of activity (e.g., 1.2-2.5 L for sedentary men, 3.2 L for modest physical activity). Further, significant water deficits can occur as a result of environmental heat exposure and physical work and may require many hours of rehydration and electrolyte intake to re-establish balance (Kenefick, et al., 2012). Dehydration of as little as 1% body mass can lead to decreases in physical and cognitive function (National Research Council, 2004).

Studies of dehydration effects on cognitive performance have yielded somewhat conflicting results (Grandjean and Grandjean, 2007). This is likely due to the range of different tasks studied, varying measures of dehydration, and the confounding variable of heat stress. Synthesis of this wide range of findings suggests that the cognitive effects of dehydration are similar to those of heat stress and are more likely to be manifest in complex tasks. Grandjean and Grandjean (2007) summarized the results of numerous prior studies, which indicate that dehydration of 2% body mass affects the following cognitive functions and tasks:

- Perception of fatigue
- Target shooting
- Sensory discrimination
- Visual-motor tracking
- Short-term memory
- Long-term memory
- Attention
- Mental arithmetic
- Choice reaction time

Lieberman (2007, 2012) points out that the lowest level of dehydration at which performance impairment is seen is not yet established, and due to the different approaches for inducing dehydration, comparison across studies is difficult. Exercise-induced dehydration may be more likely to yield performance impairment than that induced by reduction of fluid intake over time. It has also been observed that when heat stress is controlled (i.e., core body temperature is normal), cognitive impairments from dehydration can be observed (Gopinathan, et al., 1988). Additionally, self-rating scales can show reductions in such dimensions as alertness, concentration, and effort either with or without corresponding impairments on cognitive tasks (Cian, et al., 2000; Szinnai, 2005). Figure 7 (adapted from Lieberman, 2007; and Kenefick, et al., 2012) illustrates typical performance impairments in cognitive tasks at various levels of dehydration and contrasts the slowing of reaction time with dehydration to that observed in people with blood alcohol content at the legal limit for intoxication (Lieberman, 2007; Kenefick, et al., 2012).

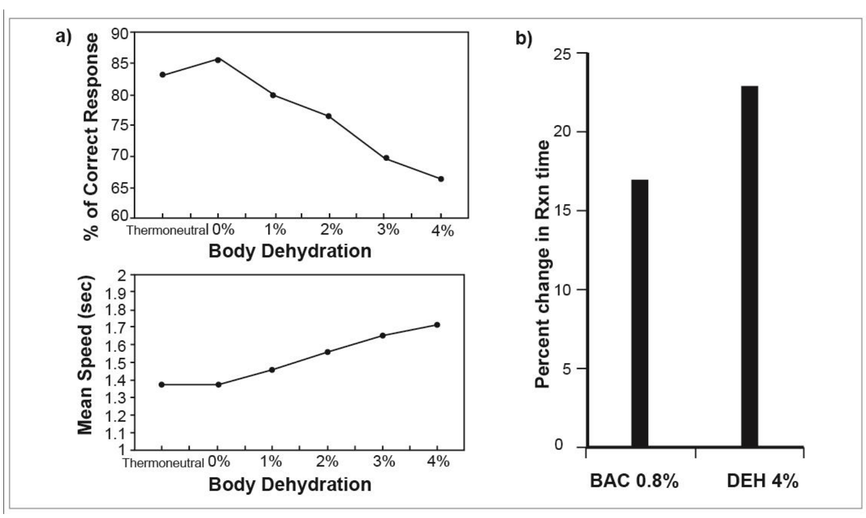


Figure 7. Decrement in correct performance and slowing of reaction time. BAC= Blood alcohol content, DEH = dehydration. (Adapted from Lieberman, 2007, and Kenefick, et al., 2012)

Work conducted by the University of Maryland and the Orange County Fire Authority (discussed in Horn, 2012) suggests that firefighters lose body mass via dehydration during firefighting (2% or more). A considerable number of firefighters also arrive at work in a dehydrated state. A systematic study of this issue was reported by Horn, et al. (2012). This group studied 35 firefighters in live firefighting drills of 3 to 4 parts, each lasting 15 to 25 minutes with 10 to 15 minutes between sessions. Fluid was available during the breaks. The results indicated that 71% of the firefighters arrived in a dehydrated state, as measured by urine analysis. During the course of the exercise, 86% of the participants lost more than 2% of their body mass through fluid loss (sweat and urine). Similar findings were obtained for pre-shift dehydration status for wild-land firefighters, although these workers achieved hydrated status over the course of their shift using either prescribed fluid intake or at-will drinking (Raines, et al., 2013).

The studies of cognitive impact and firefighter dehydration described above were based on combined weight and urinalysis methods of assessing dehydration under controlled conditions. Field assessment of dehydration before, during, or after firefighting operations will not be able to use such methods. However, comparison of various methods suggests that a combination of assessment techniques that are practical for everyday operations may be useful (Armstrong, 2007; Kenefick, et al., 2012). This would involve individual firefighters assessing their levels of thirst, urine color, and weight, using appropriate scales and guidance. As shown in Figure 8 (Cheuvront and Sawka, 2005), should all three parameters intersect, dehydration is very likely. This type of approach may provide a basis for developing self-monitoring techniques for routine use.

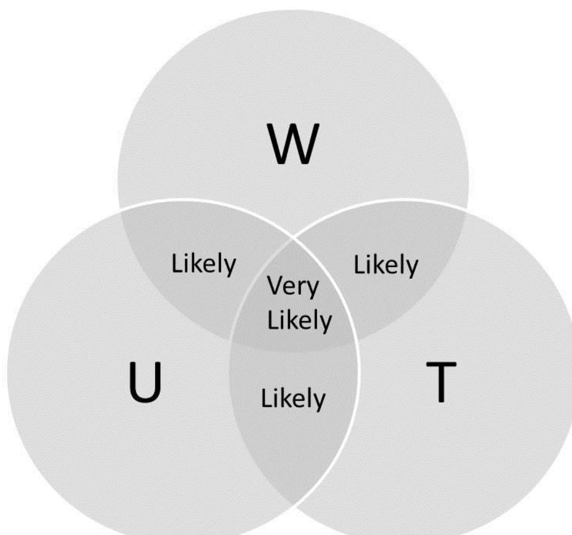


Figure 8. Three dimensions for practical assessment of dehydration status. W = weight, U = Urine, T = Thirst. (Cheuvront and Sawka, 2005)

5.0 Wearable Sensors

Wearable sensors for physiological monitoring are an integral feature of future first-responder concepts. There is considerable market research promotion of the general idea, forecasts of substantial financial opportunity, and panoply of product prototypes being evaluated in diverse application areas. While ECG has been measured in live-fire operations for over 40 years, routine use of monitoring has yet to be adopted by the first responder community. Many factors influence adoption, particularly technology maturity and user acceptance. As technology continues to improve, implementing routine physiological monitoring of first responders will be increasingly conditioned on meaningful concepts of operation, ease of use, and user acceptance. This section briefly discusses wearable sensors within this framework.

In 2004, the Massachusetts Institute of Technology Lincoln Laboratory published a technical report for the US Army concerning Warfighter Physiological and Environmental Monitoring to support the developing Land Warrior system (Shaw, et al., 2004). The report focused on defining technical requirements for near- and far-term concepts for an ensemble of equipment (sensors, networks, data processing) to develop and demonstrate a viable WPSM system. This report identified the principal technical challenges to implementation, including:

- Cost
- Size, weight, power
- Intrusiveness
- Immunity to motion artifacts
- Scalability to multiple users
- Scalability in range of operation
- Covertness
- User acceptance

A near-term system was specified, developed, and demonstrated in various stages of implementation (e.g., Buller, 2007), and work continues on development of various physiological strain indices. The 2004 report presented a selective “snapshot” of ambulatory monitoring systems and sensor technologies available for potential integration and demonstration. While a number of ambulatory monitoring systems were available commercially at that time, none were considered to be at a technology readiness level sufficient for harsh environment applications.

Pantelopoulos and Bourbakis (2010) provided a subsequent survey of wearable sensors and systems for health monitoring. These researchers defined 16 evaluation criteria for assessing performance and applied them to 19 commercially available systems, most of which measured ECG, respiration, and level of activity. The authors developed a maturity score for the various evaluation criteria for each system; this analysis suggested that none of the commercially available systems reached maximum maturity, although 7 of the 19 systems were rated “high.” The principal issues identified as requiring further work are as follows:

- Better battery technologies and energy scavenging
- Security of private information
- Improvements in miniaturization and efficiency
- Clinical validation
- Standardization and interoperability

The similarities in improvements necessary for robust application and acceptance between 2004 and 2010 are noteworthy. The need for clinical validation parallels the US Army Research Institute of Environmental Medicine position that systems need further assessment and demonstration in the target environments. The European Union smart garment for emergency responders was tested at high temperature with acceptable results (Curone, et al., 2012), but the conditions did not simulate freely moving firefighters.

The most recent comprehensive treatment of wearable sensors and systems is provided by Park, et al. (2014). While their discussion is oriented primarily in the "internet of things" framework, they do address many of the same issues that have historically limited widespread adoption of wearables: power, size, interoperability, privacy, ease of use, etc. Additionally, Park, et al. (2014) address the issue of wearable adoption from the standpoint of a business case (i.e., what are the multiple interacting processes and stakeholders that need to align in order for specific wearable systems to be adopted at a sufficient level to warrant deep investment, commercialization and marketing?). These interacting elements are depicted in Figure 9 (Park, et al., 2014). This figure illustrates that any one element is not enough, and that a key issue is articulating the need with significant input from end users and domain experts. These factors matter when considering remote physiological monitoring for first responders.

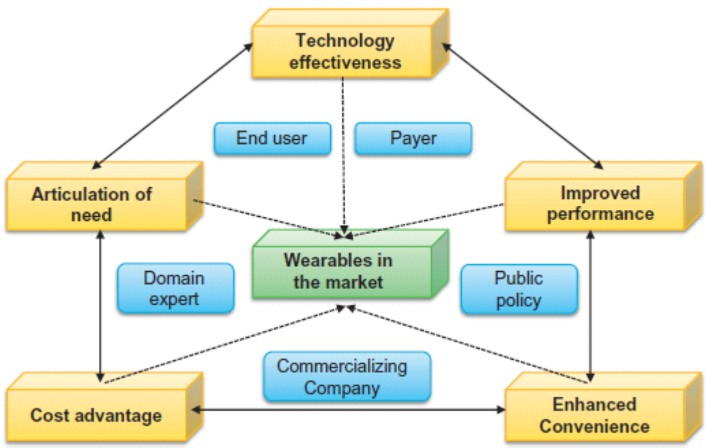


Figure 9. Developing a business case for wearables in the first responder domain. (Park, et al., 2014)

Substantial progress has been made in one domain of physiological monitoring that is relevant to operational demands on firefighters: cardiac monitoring. Walsh, et al. (2014) survey 28 different cardiac and vital sign systems that are currently available and use a range of different technologies. There is much less data available for heat stress and dehydration measurement. Core temperature measurement still relies primarily on oral, rectal, or axillary readings – all too invasive for first responder application. The core temperature "pill" has been used successfully in field work with firefighters, but expense and artifact issues remain, as well as the general undesirability of continually ingesting a foreign object for routine monitoring. Dehydration is even more difficult to address with wearable sensors, although there are research prototypes using fabric-based and skin-patch membranes for moisture collection under development (Coyle, et al., 2014; Heikenfeld, 2014). Both heat stress and dehydration may be addressed indirectly through algorithms that estimate core temperature and fluid loss – these and other processing approaches are discussed in the next section.

6.0 Outcome Measures: Algorithms, Classification, Alarms

RPMFR has been discussed primarily in terms of alerting workers or commanders to potential health problems in real-time during operations (Wood and Dadsosky, 2013) and the ability to provide health-screening and training parameters on the basis of personalized patterns over time (Batalin, et al., 2012). Both approaches share the common vision associated with wearable health sensors more generally (i.e., personalized feedback, early alerting of health professionals, early intervention for identified health conditions, and ultimately reduction of death and injury through screening and prevention). There is a continuum of application complexity and scale implied by this vision, as illustrated in Figure 10 (Kumar, et al., 2013).

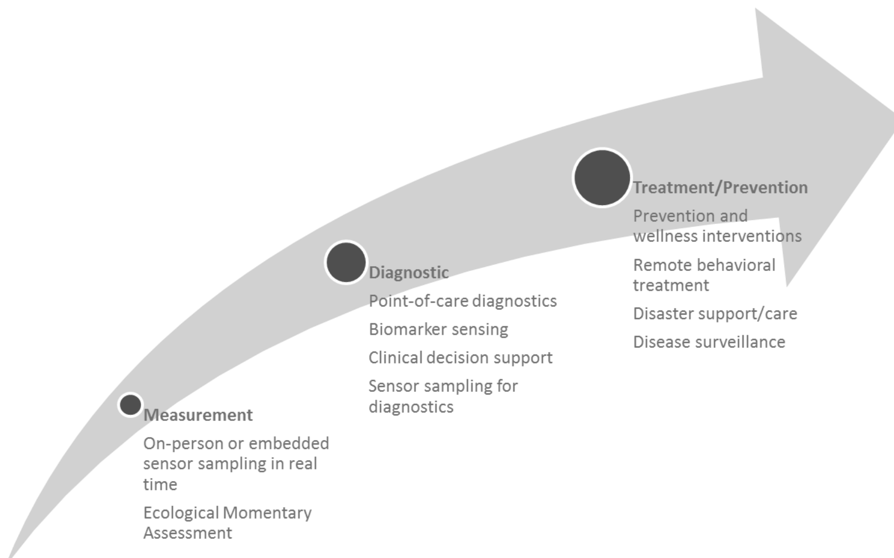


Figure 10. Application scale and complexity for wearable health sensors. (Kumar, et al., 2013)

Advances in data analysis and diagnostic algorithms lag developments in sensors and wireless transmission of data such as ECG from commonly available devices such as iPhones (Rodgers, et al., 2015). While there have been demonstrations of displays for firefighters such as the Red-Orange-Green (ROG) algorithm of Zephyr Technologies (2009), this involves primarily proof-of-concept for providing such alerts to an incident commander (i.e., measurements are reliable and the communication infrastructure can transmit the data). At the present time, there do not appear to be validated diagnostic algorithms for field application with first responders. Indeed, the state of the art for wearable sensors more broadly seems to involve demonstrating that data can be reliably collected and transmitted to a centralized health care facility server, where established software algorithms and clinical interpretations are applied (Baquero, et al., 2014), and that single-lead wireless monitoring systems provide data that match more conventional 12-lead wireless ECG measurement under simulated operational conditions (Dolezal, et al., 2014). For established ambulatory ECG monitoring systems for medical application, there is little transparency concerning algorithms or comparison to clinical gold standards; although such devices employ algorithms developed according to U.S. Federal Drug Administration (FDA) guidance (Mittal, et al. 2011).

The more general process for developing diagnostics based on physiological sensor measurements involves a multi-step process (Kumar, et al., 2013):

- Define the classification problem (e.g., use ECG to identify life-threatening situations)
- Establish training and validation data sets
- Select algorithmic approach (e.g., neural nets, autoregressive models, etc.)
- Define data time windows
- Extract features as inputs for developing classifier
- Test on training and validation data sets

Examples of this approach and application for ECG are provided by Apiletti, et al. (2009), Oresko, et al., (2010) and Sufi, et al., (2011); and have shown high rates of agreement with "truth data" from an established database, and with independent classification by diagnostic experts. It is also clear from these studies that different algorithms yield widely varying results, and in the case of heart rate risk judgments, only 50% agreement (Apiletti, et al., 2009). These studies focused on identifying specifically defined clinical conditions, whereas concepts for first responder monitoring tend to consider heart rate (relative to an externally defined maximum) as a surrogate for exertional stress that may endanger the worker.

Cardiac measures have also been used to develop predictive models of heat stress. This work has employed statistical techniques to develop predictions of core temperature during various activities, using simultaneously recorded values for validation. These models produce results that are considered accurate enough for understanding the likely thermal strain to be manifested under various field conditions (Buller, et al., 2013; Yokota, et al., 2012). Related models were developed for estimating sweat loss under various operational conditions and may be of value to the first responder community if they are appropriately contextualized and translated to actionable guidelines (Gonzalez, et al., 2009).

The challenges associated with clearly defining conditions for generating alerts and alarms based on physiological data are illustrated by the problem of "alarm fatigue" in medical settings. There is no question that physiological monitoring technology saves lives by generating alarms for life-threatening situations such as asystole (no heart beat) or extremely low blood pressure. In these cases the cost of false alarms is high, and conservative thresholds tend to be used. However, for parameters with more complex relationships to underlying conditions (including many cardiac measures, waveform, pattern, and rate), criteria and thresholds are much more ambiguous in individual cases. This results in a very high proportion of false alarms generated by monitoring equipment in clinical settings (Drew, et al., 2014; Imhoff and Kuhls, 2006). Heart rate alarms are particularly susceptible to this problem as the rate varies considerably across individuals and underlying clinical conditions and may exceed or fall below default thresholds. Across many categories of devices, alarms, and clinical conditions, the positive predictive value of alarms from physiological monitors is under 25%; meaning fewer than 1 in 4 alarms is "true" and leads to some type of intervention. Effective alarm systems should have a positive predictive value as high as possible (Sanquist, et al, 2008).

Given this context, the challenge for real-time physiological monitoring in emergency response operations is considerable. At a practical level, use of ECG for diagnosing cardiovascular disease can be considered a non-real-time activity. Although real-time data can be of use in diagnostic decisions, a substantial amount of clinical judgment is used in concert with findings from ambulatory recordings and arrhythmia detectors. The use of various cardiac measures such as heart rate reserve and recovery are employed in sports and exercise physiology (Bosquet, et al., 2008), and ECG screening in middle-aged males engaged in strenuous athletic activity has successfully identified a small proportion of high-risk underlying conditions (Menafoglio, et al., 2014). However, these applications generally required considerable post-hoc analysis through combination of ECG with other measures and information, and extension to real-time alerting would require substantial refinement of algorithms and alerting criteria. The following classification scheme may be a useful heuristic for considering potential alerting criteria for RPMFR (Imhoff and Kuhls, 2006):

- Detection of life-threatening situations (e.g., asystole, extremely low blood pressure, hypoxia). False negatives are not acceptable and immediate action is necessary to prevent death.
- Detection of imminent danger (e.g., the gradual deterioration of a monitored variable)
- Diagnostic alarms (e.g., an indication of a pathophysiologic condition, such as arrhythmia)

7.0 Practical Considerations: Reliability, Validity, Diagnostic Criteria, Regulatory Issues

Since physiological measurements in an operational context are surrogates for outcomes (worker health and safety), reliability and validity are key issues in development and application to ensure overall accuracy of performance. *Reliable* measures are repeatable under a broad range of conditions; that is, similar or identical outputs will be obtained across multiple observations and conditions of application. In other words, the range of conditions under which reliability is observed is very important when considering remote wireless monitoring in field operations, as they are inherently “noisy” environments. *Validity* is a multi-faceted concept but essentially refers to a measure actually being a faithful indicator of the condition that it is purported to represent. Heart rate as a measure, for example, is determined by many factors – exertion, emotion, physical factors – and is *potentially* an indicator of worker health and safety if combined with appropriate interpretation and context. The utility of various physiological measures for predicting immediate worker condition or overall readiness to perform is a continuing research endeavor. Does peak heart rate in field operations predict likelihood of death on the job? Relationships between heart rate changes during exercise and risk of sudden death have been demonstrated but are based on long-term data from thousands of subjects monitored during multiple points in time and have uncertain utility for application of primary prevention such as exercise training (Jouven et al., 2005; Bassan, 2005).

The use of physiological measures in operational settings to aid in determining worker safety, readiness, health risk, etc., relies on establishing “cut points” for measures. An ideal test would discriminate safe and unsafe conditions with 100% accuracy; in practice, test measures include some degree of error, and the results of “safe” and “unsafe” conditions often overlap, as shown in Figure 11 (adapted from Zou, et al., 2007). It is desirable to establish cut points such that false positives are minimized, since the credibility of the alerting system depends on high sensitivity (ability to detect the condition of interest) and specificity (ability to detect absence of condition) (Zou, et al., 2007).

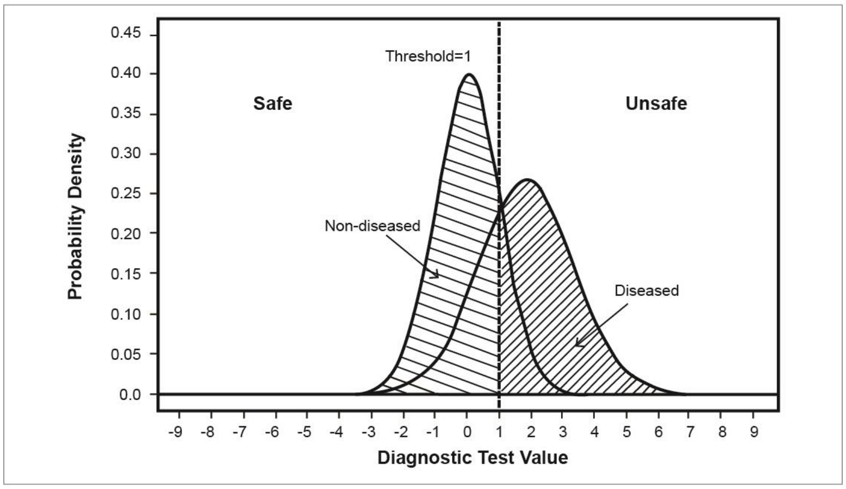


Figure 11. Hypothetical values from a diagnostic test illustrating overlapping values for safe and unsafe conditions. (Zou, et al., 2007)

Remote physiological monitoring for on-the-job safety and health assessment falls into the general category of "mHealth" applications (Cortez, et al., 2014), i.e., use of portable devices for medical purposes, including "diagnosis, treatment, or support of general health and well-being." Medical devices are regulated and approved for market in the US by the FDA, which has a pre-market approval process associated with review. mHealth technology and applications are in something of a gray zone presently, although the agency is refining guidance for developers. A fundamental concern for developers is the extent to which their mHealth applications (including remote physiological monitoring) will require FDA review for "substantial equivalence" with previously demonstrated devices or techniques. Cardiac event detection software for use in clinical settings – arrhythmia detectors and alarms – requires substantial data to be submitted demonstrating use of procedures for verification and validation with standard cardiac databases (USFDA, 2002). Currently, products being marketed for use by the operational community have received FDA approval for sensing and transmitting physiological signals (e.g., Zephyr Bioharness; AliveCor Heart Monitor). Under the current regulatory guidance, these devices appear to fall into a category in which the FDA requires review, but not at the level required for diagnostic software and devices. Should remote physiological monitoring eventually lead to specific worker health/safety alerts, it is likely that the technologies would fall into a category in which

> "Mobile apps ... become a regulated medical device (software) by performing patient-specific analysis and providing patient-specific diagnosis, or treatment recommendations. These types of mobile medical apps are similar to or perform the same function as those types of software devices that have been previously cleared or approved." (USFDA, 2013).

Thus, R&D in the RPMFR domain should be conducted in such a way that the eventual development of health and safety alerts will be able to comply with FDA requirements.

8.0 Regulating Cognitive and Physiological Responses through Self-Monitoring

Although firefighting and other emergency response operations are externally driven, recognition is growing for the role of individual differences in cognitive and physiological responses in the effective conduct of operations. A body of research has developed around the general concepts of metacognition (self-awareness and regulation) in firefighting and optimal pacing in exercise physiology which is applicable to the development of monitoring, training, and fitness approaches for emergency responders (Frye and Wearing, 2014; Tucker, 2009). This section discusses findings in these areas, with a view toward the use of remote physiological measurement and complementary cognitive de-briefing techniques to develop “resource management” training for emergency response operations.

Self-assessments of exertion have been reported to be superior to specific physiological measures in various circumstances (NRC, 2004). Although there are limitations that sometimes occur due to lack of training or severe sleep deprivation, a number of studies show the utility of the Rating of Perceived Exertion (RPE) scale for assessing physiological strain. Perceived exertion reflects the overall sensation of effort, with physiological variables such as heart rate, blood pressure, and temperature contributing to it. RPE is considered a “gestalt” or whole-person measure of physical strain and has been shown to be a better predictor of exercise performance than heart rate or other single measures in certain circumstances. In firefighting simulations, RPE shows a reasonably high correlation with thermal stress as measured by heart rate and core temperature (Petruzello, et al., 2009).

More extensive reviews of studies employing simultaneous physiological and self-rating measures suggest that people can be trained to systematically pay attention to the sensations that contribute to perceived exertion (NRC, 2004). Further, self-assessment and skills training has been shown to lead to improved performance – more so than training using a single physiological measure such as heart rate as a basis (e.g., Koltyn and Morgan, 1992; Barwood, et al., 2008). These improvements tend to be achieved through adopting preferred intensities and pace based on the anticipated duration of exercise or work. Research reported by Swart, et al. (2012) demonstrates that perceived physiological exertion based on the RPE scale can be distinguished from *task effort and awareness*, with the latter being a cognitive interpretation of the relative match between physical output requirements and the effort needed to maintain that output. This research suggests that optimum pacing is a result of an “anticipatory feed forward” neurocognitive process, based on initial assessment of exertion requirements and continual reassessment.

The cognitive aspects of firefighting have been studied primarily for the role of incident commanders (e.g., Frye and Wearing, 2014). This work identified general patterns in how commanders make decisions and assess overall situations. Research aimed at understanding the specific decisions made by individual firefighters on the ground and in teams was conducted by Fern, et al. (2008) to better elucidate the specific information requirements to support those decisions. The general model resulting from this work is shown in Figure 12 (Fern, et al., 2008). Detailed tables in their paper delineate 25 individual decision categories across the functional areas of situation assessment, route management, threat reduction, resource management, and extraction. Additionally, over 70 specific information requirements can be involved for decisions made across distributed teams of firefighters.

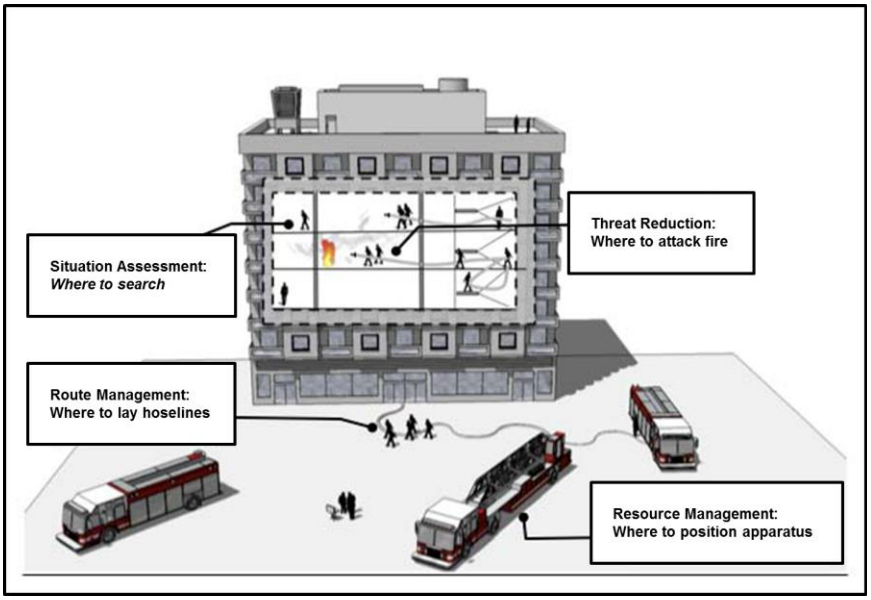


Figure 12. Functional decisions made by firefighters on the ground. (Fern, et al., 2008)

It is well-established that decisions made under stress – such as firefighting – are more susceptible to cognitive biases or errors either in command situations or at the individual level. These errors include becoming overly focused on a single aspect of a situation, failing to account for what might happen next, failing to make critical decisions in the interest of maintaining situational awareness, and persisting in particular actions when the situation changes (Frye and Wearing, 2014). Research with operational firefighters and incident commanders, both in field and training situations, suggests that awareness of cognitive and emotional (stress) tendencies can be developed, via debriefings, retrospective think-aloud protocols, and cued recall based on post-event analysis of physiological data (McLennan, et al., 2005; Brooks, 2014; Gomes, et al., 2012). Further, the widespread success of metacognitive approaches such as cockpit resource management and team situational awareness training, and the developing application of symptom- and strategy-based techniques for addressing worker fatigue, offers an avenue for combining cognitive and physiological approaches to address the operational demands of firefighting in the overall context of self-regulation.

9.0 Conclusions and Research Recommendations

The research reviewed in this paper suggests that a programmatic approach to remote physiological monitoring for first responders will be necessary to address the challenges posed by the rigors of the operational environment, and the relative immaturity of *systems and operations concepts,* as distinct from individual technologies. This final section summarizes conclusions that can be drawn from the review and proposes research approaches that can be undertaken by the DHS RTA to foster technology and system development and dissemination.

The following conclusions are supported:

- Remote monitoring and transmission of cardiac parameters for first responders is feasible and accurately reflects the physical demands of the job.

- Remote monitoring of heat stress is *possible* but not particularly practical.
- Remote monitoring of dehydration is not currently feasible on the basis of existing sensor capability.
- Software algorithms and outcome measures for physiological signals are relatively immature and require support from clinical experts.
- Near- or supra-maximal heart rate, increased core temperature, and dehydration are routinely encountered in firefighting operations.
- Operational personnel are generally aware of levels of exertion, heat stress, and dehydration when measured by self-report.
- The physiological impacts of operational demands can impair worker cognitive functioning.
- Awareness-based models of physiological and cognitive performance impacts can be taught and can influence subsequent activity.

The initial concepts for RPMFR were inspired by the formulation and demonstrations of components of the WPSM system. Early work in this program started in the late 1990s, with prototypes demonstrated in the early 2000s, and subsequent component and data processing refinements ensued. The WPSM has not yet been implemented as a system for routine use, despite the substantial resources and continuing need within the DOD. Research sponsored by DOD continues to develop data analysis algorithms that employ heart rate and other environmental variables for the prediction of thermal stress. Similarly, the ability to record and transmit physiological variables from first responders has been available for a considerable period, but has yet to be incorporated as a routine aspect of turnout gear and post-operation analysis or used for fitness and health guidance.

The reasons for the current lack of systematic use of RPMFR are multiple, some of which are technical, such as sensor size, weight, battery life, etc. However, these problems are rapidly diminishing, and at least one system – the Zephyr Bioharness – has been used multiple times in live fire operations and continues to be employed in other venues such as sports training. More problematic is the lack of clearly defined user needs, system concepts, and outcome measures that can be effectively employed to improve worker safety and health. Although various national standards organizations such as NFPA recommend health screening and lifestyle adaptations to address cardiovascular risk, adopting such approaches remains voluntary and cost is an issue. Further, even major metropolitan areas have somewhat fragmented first response organizations, with no single entity having the resources to devote to developing, fielding, and validating remote monitoring approaches shown to work in demonstration experiments. As a result, a cycle of individual project-based demonstrations occurs periodically but does not lead to sustained system refinement based on prior research findings[3]. This is less so in the DOD research, where incremental progress has been made in developing physiological strain indices. Even this work, though, is not at a point where large-scale fielding of systems for use on a routine basis is practical. The remainder of this section addresses the following question: *What are the programmatic R&D steps necessary to develop remote physiological monitoring for first responders to the point where it becomes a useful and routine part of everyday operations?*

[3] This could be counterproductive. For example, the Zephyr Bioharness red-orange-green algorithm employs heart rate maxima identified in University of Maryland field research as the basis for defining the red-orange-green safety zones associated with their system. No medical validation of these heart rate levels substantiates their use as thresholds for "safety" zones of performance, yet promotional material for the product implies such utility.

A number of specific R&D tasks can lead to further progress in the development and application of RPMFR. A good starting point for considering the necessary R&D components for programmatic development of RPMFR is the stakeholder process diagram shown in Figure 9. Although this figure has no implied entry point or time basis, it is tempting to think that Articulation of Need by end users and domain experts would drive technology development in commercial companies and research organizations. This would lead to cost reductions and more effective and convenient technologies available to meet the need. Alternatively, public policy would drive articulation of the need through increasing the salience of the specific problem at hand (e.g., responder health and safety) and would engender payment incentives for employing specific technologies. This latter scenario is essentially what occurred in the post-9/11 era with various screening technologies at airports.

For RPMFR, a need has only been rudimentarily articulated through the priority list of the IAB. Public policy encourages responder health and safety, but specific performance requirements are not mandated. Thus, the specific user needs or use cases in this area tend to be defined on the basis of commercial developers and research organizations. In the case of RPMFR, the need has generally revolved around the notion of reducing cardiac deaths. This is an important consideration, but may not be the primary or only potential use of remote monitoring. Instead, remote monitoring may represent a training and feedback tool initially, with cardiovascular health screening and improvement being a longer-term prospect. The following paragraphs describe specific research tasks that would comprise an overall program to develop RPMFR to achieve routine application in operations. The main thrust of the program is clear definition of how RPMFR will be put to work in routine practice, conducting field research and large-scale data collection to enable development of analytic processes, and evaluation of training and feedback processes implemented as a result of routine physiological monitoring in operations. A reasonable time frame for the entire set of projects is 36 months.

9.1 Articulate the need for RPMFR

A limiting factor in development of RPMFR for routine application is lack of a clearly defined need. Many demonstrations of remote monitoring of cardiac parameters for firefighters generally have been carried out to quantify the physiological work requirements of the job in order to develop better training, fitness standards, and materiel evaluation. In these types of applications, physiological monitoring represents a dependent variable that can be used to assess work demands, rather than a diagnostic screening tool or performance feedback and enhancement system.

The research community and commercial vendors for remote monitoring systems suggest that reducing on-duty cardiac deaths is a principal need, or more generally ensuring that operational personnel do not exceed “limits” that would endanger their lives or those of others. While these are desirable goals, more information is needed to understand the specific needs of first responder organizations that can be addressed with RPMFR. Thus, we suggest that a needs assessment be undertaken as the initial step in developing an integrated R&D program. The needs assessment would focus on information gathering from a range of sources, including medical, safety, and health officials of first responder organizations, first-line supervisory personnel, and individual operational personnel. The needs assessment would also focus on discerning how existing health and safety systems can be enhanced for reducing risk and improving health and fitness. Certain issues may surface, such as the lack of periodic screening as suggested by NFPA, disparity between fitness requirements for selection versus maintenance of those standards after hiring, and a general lack of knowledge regarding physiological health. The needs assessment will likely also identify a broader range of issues related to on-the-job performance in high demand situations, including impairments in situational awareness, communication and team dynamics – these issues tend to be discussed among responder personnel anecdotally, and more systematic assessment is warranted. The overall goal of the needs assessment is to get beyond the aspirational goals described by the research community and commercial vendors, to set the stage for defining operational concepts to actually achieve those goals. If we have recorded cardiac parameters in live fire operations for more than 40 years, why are we not making more use of that capability?

9.2 Develop Operations Concepts (CONOPS)

The needs assessment will identify issues not currently addressed by existing processes and technologies within first responder organizations. These *unmet needs* will require novel solutions. We assume that while existing technologies, such as wearable sensors, have the *potential* to address the needs, those technologies have not been incorporated into a workable and sustainable process. Developing operations concepts for RMPMR requires addressing the fundamental issues of end user, payer, convenience, and cost effectiveness.

The research demonstrations reported above suggest that first responders are willing and interested in using remote monitoring. What has not been developed is an organizational model for how such technologies would become a routine part of responder operations. The DHS-funded PHASER program (Batalin, et al., 2013) has begun to address these issues, but substantially more work needs to be done in this area, including defining end uses for the physiological data (e.g., health screening, post-event debriefing and analysis, guiding physical training, use of symptoms or feedback for self-monitoring in operations, etc.), as well as the technical and organizational support necessary to use the data in various ways (rapid, uncomplicated and valid analysis, quick turn-around interpretation, expert facilitation and guidance for self-monitoring and cognitive skills training, easy-to-adopt and follow fitness training regimens, etc.).

We see the development of operations concepts (CONOPS) as a more detailed process than articulating the need. Interaction with resources from the RTA responder community will be necessary on a more intensive basis to fully understand the parameters of how remote monitoring can be put to work. Engaging with health and safety, first-line supervisory personnel, and potentially union representatives will be necessary to identify practical approaches. Validating the concepts with members of the operational community not involved in their development will help to identify issues not considered and approaches to make the CONOPS more generally applicable. The results of this task will set requirements for subsequent research tasks to enable the RPMFR operations concepts.

9.3 Design programs and teams of experts

Validated CONOPS will require specific operational programs and expertise to implement and evaluate. This task is concerned with designing the overall program for how CONOPS will be implemented; identifying and recruiting operational, technical, and research expertise; and formulating an overall plan. For example, if acceptable CONOPS entail routine physiological recording and debriefing about cognitive and team performance, this will require a systematic process and technical expertise for implementation. Thus, this research task is somewhat dependent on the results of the needs assessment and CONOPS activities, but in general will entail the following activities:

- Specify workflow, data requirements, and actions required of first-line operational personnel – what will they have to do, how often, and how will this be embedded in the work shift?
- Define the process for providing personalized and group feedback regarding physiological variables and operational performance.
- Link the feedback process to intervention activities such as physical training, lifestyle modification, self-monitoring, and cognitive skills training.
- Determine the extent to which existing training material and activities can incorporate remote monitoring and operational feedback information.
- Define expertise required to collect, analyze, develop personalized feedback, and deliver training or coaching.
- Recruit experts from within operational first responder organizations, commercial developers, research organizations, and academic groups.

We can expect that diverse expertise will be required, including training system development, exercise physiology, cardiovascular medicine, statistics, and various engineering/technical disciplines to implement a robust remote monitoring and analysis system.

9.4 Screen and select technologies

This task entails analyzing and selecting the wearable sensors and remote monitoring network technologies necessary to provide the data that will enable analysis and application. As reported above, many surveys have been performed but it is safe to assume that whatever is published is already out of date, due to the rapid rate of engineering change. The fundamental challenge in selecting technologies is to ensure that they have been adequately validated for providing data to enable the desired application. Cardiac parameters provide a good example: while the Zephyr Bioharness has been shown to provide *heart rate* data equivalent to a standard 12-lead ECG that would be used for clinical purposes, is the signal adequate for addressing more detailed health screening based on ECG?

The wearable sensor field is widely populated with start-up organizations. The screening and selection task should focus on vendors that are already established and preferably those with demonstrated capability in operational settings. FDA approval of the devices for transmission of medical data would be a further benefit. A primary consideration in this task is to ensure that selected technologies have a track record that will allow incremental improvement in applications, rather than using government R&D funding to support basic development.

9.5 Collect operational data

Developing robust, sustainable RMPFR applications ultimately depends on demonstrating utility in operational circumstances. Thus, there is a need for large-scale data collection of remote monitoring data in conjunction with a variety of other information to support interpretation, such as individual life-style/health data and critical event analysis of operations. It would be desirable to collect data longitudinally in as large a sample as feasible, across diverse operations. From a practical standpoint, one or more large metropolitan fire departments would be likely candidates. Prior field research has shown the feasibility of collecting physiological data in live fire circumstances; a principal challenge in this task will be to collect the supporting critical event analysis and individual firefighter self-monitoring data. Use of the “embedded researcher” model employed by the Indiana research group (Stickford and Brown, 2008) is recommended as a way to build operational expertise for the researchers to aid in developing analytics and interpretation.

9.6 Develop analytics

Interpretation of remote physiological data is a weak element that currently limits meaningful application of the technology. Diagnosing underlying cardiovascular pathology is still a clinical process requiring non-real-time consolidation of multiple pieces of information in addition to physiological signals. It is unlikely that a three-year research program, even with data from hundreds of participants, is going to change this approach. However, with sufficient data, incremental progress can occur in analysis and interpretation that may yield benefit to the first responder community.

The current disparity in analytics versus application is shown by the work of Dolezal, et al. (2014); these researchers showed that 12-lead ECG, remotely transmitted to distant experts for off-line interpretation was able to identify an instance of underlying cardiovascular disease in a firefighter. This was a non-real-time process, required application of a previously developed ECG interpretation algorithm and validation by a human expert, blinded to the individual respondent characteristics. Moving beyond this state of affairs will require developing a more elaborated data model, to include physiological signals, temporal information, critical operational event information, and individual lifestyle/health data. Further, analytics should focus not only on physiological/health data and outcomes, but also on *process* variables such as team performance, situational awareness, cognitive skills, etc.

9.7 Develop feedback and training

Results from the data collection and analysis tasks will enable the development of diverse feedback and training material for enhancing first responder health and safety. While it is difficult to be specific about the types and means of feedback and training in advance of research results, we can anticipate development of certain types of material, including:

- Individual physiological response profiles for specific operations and across operations
- Personalized health and fitness recommendations and means for tracking
- Metacognitive skills training to enhance self-regulation based on awareness of event characteristics and real-time physiological data

These feedback and training elements should be continually incorporated into ongoing safety programs as the analysis activity proceeds.

9.8 Evaluate impact

The outcomes of the research program elements described here are intended to improve the health and safety of first responder personnel. Thus, evaluation is warranted in a fashion appropriate to the state of the program. We do not anticipate that a “summative” evaluation will be possible in the time frame described for the main research activities, i.e., drawing conclusions regarding specific health and safety impacts in a "before and after" type of model. Instead, a "formative" type of evaluation would be more appropriate to gain an understanding of the various process impacts of implementing RPMFR. The results of a formative evaluation can lead to development of a general, sustainable approach for routine use of remote monitoring.

In parallel with the formative evaluation throughout the program, effort should be directed to establish data collection processes that would permit the longer duration analyses necessary for a summative evaluation study. This would include health and lifestyle monitoring of responders, periodic assessment of critical incidents and application of various self-regulation skills, and analyses of reportable accidents and injuries within the framework of performance-shaping factors (risk factors, cognitive demands). Over time, modifications and enhancements to event and accident analysis procedures may be required, as the "human factor" is involved a large percentage of the time, but investigation techniques are not sufficiently refined to identify root causes.

9.9 Embed research results and materials within a dissemination pathway for broader application

Development of various products, such as self-monitoring training and countermeasure tools, assumes effective ways to distribute the material. A research issue to be addressed concerns the mechanisms and responsibilities for an online repository, particularly a website that is routinely maintained and can provide access to the various materials. Experience, however, has shown that a website is insufficient for widespread outreach on its own. In addition, the website needs to be made broadly available through other sources routinely contacted by first responder organization safety personnel. Principal organizations for this type of function include the NFPA and similar professional groups for police and emergency medical responders.

10.0 References

Angerer, P., Kadlez-Gebhardt, S, Delius, M., Raluca, P., & Nowak, D. (2008). Comparison of cardiocirculatory and thermal strain of male firefighters during fire suppression to exercise stress test and aerobic exercise testing. *American Journal of Cardiology, 102*(11), 1551-1556. http://dx.doi.org/10.1016/j.amjcard.2008.07.052.

Apiletti, D., Baralis, E., Bruno, G., & Cerquitelli, T. (2009, May). Real-time analysis of physiological data to support medical applications. *IEEE Transactions on Information Technology in Biomedicine*, *13*(3), 313-321.

Armstrong, L.E. (2007). Assessing hydration status: The elusive gold standard. *Journal of the American College of Nutrition*, *26*(5), 575S-584S.

Baker, J., Grice, J., Roby, L., & Matthews, C. (2000). Cardiorespiratory and thermoregulatory response of working in fire-fighter protective clothing in a temperate environment. *Ergonomics*, *43*(9), 1450-1358.

Baquero, G.A., Banchs, J.E., Ahmed, S., Naccarelli, G.V., & Luck, J.C. (2014). Surface 12 lead electrocardiogram recordings using smart phone technology. *Journal of Electrocardiology*, *48*(1), 1-7. doi:10.1016/j.jelectrocard.2014.09.006

Barnard, R., & Duncan, H. (1975, April). Heart rate and ECG responses of fire fighters. *Journal of Occupational Medicine*, *17*(4), 247-250.

Barwood, M.J., Thelwell, R.C., & Tipton, M.J. (2008). Psychological skills training improves exercise performance in the heat. *Medicine and Science in Sports and Exercise*, *40*(2), 387- 396.

Bassan, M.M. (2005). Letter to the Editor. *New England Journal of Medicine*, *353*, 734-735. doi: 10.1056/NEJM200508183530717

Beatty, J., Greenberg, A., Deibler, W. P., & O'Hanlon, J. F. (1974). Operant control of occipital theta rhythm affects performance in a radar monitoring task. *Science*, *183*(4127), 871–873.

Bosquet, L., Merkari, S., Arvisais, D., & Aubert, A.E. (2008, December). Is heart rate a convenient tool to monitor over-reaching? A systematic review of the literature. *British Journal of Sports Medicine*, *42*(9), 709-714. DOI: 10.1136/bjsm.2007.042200

Brooks, B. (2014). Coping ugly: Errors, decisions, coping and the implications for emergency management training. In C. Owen (Ed.), *Human Factors in Emergency Management* (pp. 171-194). Burlington, VT: Ashgate Publishing Limited.

Brown, J and Stickford, J. (2008). *Physiological stress associated with structural firefighting observed in professional firefighters*. Retrieved from http://www.indiana.edu/~firefit/pdf/Final%20Report.pdf

Buller, M.J., Tharion, W.J., Cheuvront, S.N., Montain, S.J., Kenefick, R.W., Castellani, J., Latzka, W.A., Roberts, W.S., Richter, M., Jenkins, O.C., & Hoyt, R. (2013). Estimation of human core temperature from sequential heart rate observations. *Physiological Measurement*, *34*(7), 781-798. doi: 10.1088/0967-3334/34/7/781

Buller, M.J., Tharion, W.J., Karis, A.J., Santee, W.R., Mullen, S.P., Blanchard, L.A. & Hoyt, R.W. (2007, October). *Demonstration of real-time physiological status monitoring of encapsulated 1st civil support team-weapons of mass destruction (CST-WMD) personnel* (US Army Research Institute of Environmental Medicine Technical Report T08-01). Natick, MA: US Army Research Institute of Environmental Medicine.

Bureau of Labor Statistics (2011). Firefighter Factsheet. *Injuries, Illnesses, and Fatalities*. Retrieved from http://www.bls.gov/iif/oshwc/cfoi/osar0017.htm

Cheuvront, S.N., & Sawka, M.N. (2005). Hydration assessment of athletes. *Sports Science Exchange*, *18*(2), 1-5. Retrieved from http://www.gssiweb.org/Article/sse-97-hydration-assessment-of-athletes.

Cian, C., Koulmann, N., Barraud, P.A., Raphel, C., Jimenez, C., & Melin, B. (2000). Influence of variations in body hydration on cognitive function: Effect of hyperhydration, heat stress, and exercise-induced dehydration. *Journal of Psychophysiology*, *14*(1), 29-36.

Cortez, N.G., Cohen, G., & Kesselheim, A.S. (2014). FDA Regulation of mobile health technologies. *The New England Journal of Medicine, 371*(4), 372-379.

Coyle, S., Curto, V.F., Benito-Lopez, F., Florea, L., & Diamond, D. (2014). Wearable Bio and Chemical Sensors. In E. Sazonov and M.R. Neuman (Eds.), *Wearable Sensors: Fundamentals, Implementation and Applications* (pp. 65-83). Amsterdam: Elsevier Science.

Curone, D., Secco, E.L., Caldani, L., Lanata, A., Paradiso, R., Tognetti, A., & Magenes, G. (2012). Assessment of sensing fire fighters uniforms for physiological parameter measurement in harsh environment. *IEEE Transaction on Information Technology in Biomedicine, 16*(3), 501-511. doi: 10.1109/titb.2011.2182615

Dolezal, B. A., Boland, D. M., Carney, J., Abrazado, M., Smith, D. L., & Cooper, C. B. (2014). Validation of heart rate derived from a physiological status monitor-embedded compression shirt against criterion ECG. *Journal of Occupational and Environmental Hygiene, 11*(12), 833-839. doi: 10.1080/15459624.2014.925114

Dolezal, B.A., Abrazado, M., Batalin, M.A., Smith, D., & Cooper, C.B. (2014). Deployment of remote advanced electrocardiography for improved cardiovascular risk assessment in career firefighters. *Telemed J E Health, 20*(7), 660-663. doi: 10.1089/tmj.2013.0321

Drew, B.J., Harris, P., Zegre-Hemsey, J.K., Mammone, T., Schindler, D., Salas-Boni, R., Yong, B., Adelita, T., Ding, Q. & Hu, X. (2014). Insights into the problem of alarm fatigue with physiologic monitor devices: A comprehensive observational study of consecutive intensive care unit patients. *PLOS One, 9*(10), 1-23. doi: 10.1371/journal.pone.0110274

Fahy, R.F., LeBlanc, P.R., & Molis, J.L. (2014). Firefighter Fatalities in the United States – 2013. *National Fire Protection Association Technical Report*. Retrieved from http://www.nfpa.org/~/media/Files/Research/NFPA%20reports/Fire%20service%20statistics/osff f.pdf

Federal Emergency Management Agency (2008, February). *U.S. Fire Administration Emergency Incident Rehabilitation*. Retrieved from http://www.usfa.fema.gov/downloads/pdf/publications/fa_314.pdf

Fern, L., Trent, S., & Voshell, M. (2008). A functional goal decomposition of urban firefighting. *Proceedings of the 5th International ISCRAM Conference.* F. Fiedrich and B. Van de Walle (Eds.).

Foster, J., & Roberts, G. (1994). *Measurements of the fire-fighting environment* (Research Report No. 61). Central Fire Brigades Advisory Council, Scottish Fire Brigades Advisory Council, Joint Committee on Fire Research.

Friedl, K.E. (2004). Predicting and protecting performance using metabolic monitoring strategies: It's all wet stuff anyway, isn't it? Workshop manuscript for *Monitoring Metabolic Status: Predicting Decrements in Physiological and Cognitive Performance* (pp. 237-247). Washington, DC: National Academy Press.

Frye, L.M., & Wearing, A.J. (2014). What were they thinking? A model of metacognition for bushfire fighters. In C. Owen (Ed.), *Human Factors in Emergency Management* (pp. 57-58). Burlington, VT: Ashgate.

Gomes, P., Kaiseler, M., Querios, C., Oliveira, M., Lopes, B., & Coimbra, M. (2012). Vital Analysis: Annotating sensed physiological signals with the stress levels of first responders in action. *Proceedings of the 34th Annual International Conference of the IEEE EMBS, 2012*, 6695-6698. doi: 10.1109/embc.2012.6347530

Gonzalez, R.R, Cheuvront, S.N., Montain, S.J., Goodman, D.A., Blanchard, L.A., Berglund, L.G., & Sawka, M.N. (2009). Expanded prediction equations of human sweat loss and water needs. *Journal of Applied Physiology*, *107*(2), 379-388.

Gopinathan, P.M., Pichan, G., & Sharma, V.M. (1988). Role of dehydration in heat stress-induced variations in mental performance. *Archives of Environmental Health*, *43*(1), 15-17.

Grandjean, A.C., & Grandjean N.R. (2007). Dehydration and cognitive performance. *Journal of the American College of Nutrition*, *26*(Suppl. 5), 549S-554S.

Guidotti, T.L. (1992). Human factors in firefighting: ergonomic-, cardiopulmonary-, and psychogenic stress-related issues. *International Archives of Occupational and Environmental Health*, *64*(1), 1-12. doi: 10.1007/BF00625945

Hancock, P.A., & Vasmatzidis, I. (2003). Effects of heat stress on cognitive performance: the current state of knowledge. *International Journal of Hyperthermia*, *19*(3), 355-372. doi: 10.1080/0265673021000054630

Heikenfeld, J. (2014, November). Let them see you sweat. *IEEE Spectrum*, 46-63.

Hockey, R. (2013). *The Psychology of Fatigue: Work, Effort and Control*. New York: Cambridge University Press.

Holter, N.J. (1961). New method for heart studies. *Science*, *134*(3486), 1214-1220.

Horn, G.P., Blevins, S., Fernhall, B., & Smith, D.L. (2013). Core temperature and heart rate response to repeated bouts of firefighting activities. *Ergonomics, 56*(9), 1456-1473. doi: 10.1080/00140139.2013.818719

Horn, G.P., DeBlois, J., Shalmyeva, I., & Smith, D.L. (2012). Quantifying dehydration in the fire service using field methods and novel devices. *Prehospital Emergency Care*, *16*(3), 347-355. doi:10.3109/10903127.2012.664243

Imhoff, M., & Kuhls, S. (2006). Alarm algorithms in critical care monitoring. *Anesthesia and Analgesia*, *102*(5), 1525-1537. doi: 1510.1213/1501.ane.0000204385.0000201983.0000204361

Ives, J.R., & Woods, J.F. (1975). Four-channel 24-hour cassette recorder for long-term EEG monitoring of ambulatory patients [Technical contribution]. *Electroencephalography and Clinical Neurophysiology, 39*(1): 88-92.

Jouven, X., Empana, J. P., Schwartz, P. J., Desnos, M., Courbon, D., & Ducimetière, P. (2005). Heart-Rate Profile during Exercise as a Predictor of Sudden Death. *New England Journal of Medicine*. *352*(19), 1951-1958. doi: 10.1056/NEJMoa043012

Karter, M.J., & Molis, J.L. (2014). US Firefighter Injuries - 2013. *National Fire Protection Association*. Retrieved from http://www.nfpa.org/~/media/Files/Research/NFPA%20reports/Fire%20service%20statistics/osffinjuries.pdf

Kenefick, R.W., Cheuvront, S.N., Leon, L., & O'Brien, K. (2012). Dehydration and Rehydration. In P. S. Auerbach (Ed.), *Wilderness Medicine Textbook*. Philadelphia, PA: Elsevier Mosby.

Koltyn K.F., & Morgan W.P. (1992). Efficacy of perceptual versus heart rate monitoring in the development of endurance. *British Journal of Sports Medicine, 26*(2), 132-134.

Kumar, S., Nilsen, W. J., Abernethy, A., Atienza, A., Patrick, K., Pavel, M., Riley, W.T., Shar, A., Spring, B., Spruijt-Metz, D., Hedeker, D., Honavar, V., Kravitz, R., Lefebvre, R.C., Mohr, D.C., Murphy, S.A., Quinn, C., Shusterman, V., & Swendeman, D. (2013). Mobile health technology evaluation: The mHealth evidence workshop. *American Journal of Preventive Medicine*, *45*(2), 228-236. doi: 10.1016/j.amepre.2013.03.017

Lemon, P.R.W., & Hermiston, R.T. (1977). Physiological profile of professional fire fighters. *Journal of Occupational Medicine*, *19*(5), 337-340.

Lieberman, H.R. (2007). Hydration and cognition: A critical review and recommendations for future research. *Journal of the American College of Nutrition*, *26*(Suppl. 5), 555S-561S. doi: 10.1080/07315724.2007.10719658

Lieberman, H.R. (2012). Methods for assessing the effects of dehydration on cognitive function. *Nutrition Reviews*, *70*(Suppl. 2), S143-S146. doi: 10.1111/j.1753-4887.2012.00524.x

Manning, J.E., & Griggs, T.R. (1983). Heart rates in firefighters using light and heavy breathing equipment: similar near-maximal exertion in response to multiple work load conditions. *Journal of Occupational Health*, *25*(3), 215-218.

McLennan, J., Pavlou, O., & Omodei, M.M. (2005). Cognitive control processes discriminate between better versus poorer performance by fire ground commanders. In H. Montgomery, R. Lipshitz, & B. Brehmer (Eds.), *How Professionals Make Decisions* (pp. 2009-2022). Mahwah, NJ: Lawrence Erlbaum Associates.

McLennan, J., Strickland, R., Omodei, M., & Suss, J. (2014). Stress and wildland firefighter safety-related decisions and actions. In C. Owen (Ed.), *Human Factors in Emergency Management* (pp. 19-33). Burlington, VT: Ashgate Publishing.

Menafoglio, A. Valentino, M., Porretta, A.P., Foglia, P., Segatto, J.M., Patrick Siragusa, P., Pezzoli, R., et al. (2014). Cardiovascular evaluation of middle-aged individuals engaged in high-intensity sport activities: Implications for workload, yield and economic costs. *British Journal of Sports Medicine*. doi:10.1136/bjsports-2014-093857

Mehta, R.K., & Parasuraman, R. (2013). Effects of mental fatigue on the development of physical fatigue: A neuroergonomic approach. *Human Factors*, *56*(4), 645-656. doi:10.1177/0018720813507279

Mittal, S., Movsowitz, C., & Steinberg, JS. (2011). Ambulatory external electrocardiographic monitoring. *Journal of the American College of Cardiology*, *58*(17), 1741 – 1749.

National Research Council. (2004). *Monitoring Metabolic Status: Predicting Decrements in Physiological and Cognitive Performance*. Washington, DC: National Academy Press.

Noakes, T.D. (2012). Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. *Frontiers in Physiology*, *3*, 1-13. doi: 10.3389/fphys.2012.00082

Noakes, T.D., St. Clair Gibson, A., & Lambert, E.V. (2005). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *British Journal of Sports Medicine*, *39*(2), 120-124. doi: 10.1136/bjsm.2003.010330

Oresko, J.J., Duschl, H., & Cheng, A.C. (2010). A wearable smartphone-based platform for real-time cardiovascular disease detection via electrocardiogram processing. *IEEE Transactions on Information Technology in Biomedicine*, *14*(3), 734-740. doi: 10.1109/titb.2010.2047865

Pantelopoulos, A., & Bourbakis, N.G. (2010). A survey on wearable sensory-based systems for health monitoring and prognosis. *IEEE Transactions on Systems, Man, and Cybernetics – Part C: Applications and Reviews*, *40*(1), 1-12. doi: 10.1109/TSMCC.2009.2032660

Park, S., Chung, K., & Jayaraman, S. (2014). Wearables: Fundamentals, advancements and a roadmap for the future. In E. Sazonov and M.R. Neuman (Eds.), *Wearable Sensors: Fundamentals, Implementation and Applications* (pp. 1-23). Amsterdam: Elsevier.

Petruzzello, S.J., Gapin, J.I., Snook, E., & Smith, D.L. (2009). Perceptual and physiological heat strain: Examination in firefighters in laboratory- and field-based studies. *Ergonomics*, 52(6), 747-754. doi: 10.1080/00140130802550216

Pollack, C.V. (2009). Wireless cardiac event alert monitoring is feasible and effective in the emergency department and adjacent waiting areas. *Critical Pathways in Cardiology*, *8*(1), 7-11. doi: 10.1097/HPC.0b013e3181980f8b

Raines, J., Snow, R. J., Peterson, A., Harvey, J., Nichols, D., & Aisbett, B. (2013). The effect of prescribed fluid consumption on physiology and work behavior of wildfire fighters. *Applied Ergonomics*, *44*(3), 404-413.

Rodgers, M.M., Pai, V.M., & Conroy, R.S. (in press). Recent advances in wearable sensors for health monitoring. *IEEE Sensors Journal*.

Schneider, R.A. (1968). A fully automatic portable blood pressure recorder. *Journal of Applied Physiology*, *24*(1), 115-118.

Sanquist, T.F., Doctor, P., and Parasuraman, R. (2008). Designing effective alarms for radiation detection in homeland security cargo screening. *IEEE Systems, Man and Cybernetics, Part C: Applications and Reviews*, 38(6): 856-860.

Sem-Jacobsen, C.W. (1959). Electroencephalographic study of pilot stresses in flight. *Journal of Aviation Medicine*, *30*, 787-801.

Shaw, G.A., Siegel, A.M., Zogbi, G., & Opar, T.P. (2004). Warfighter physiological and environmental monitoring: A study for the US Army Research Institute in Environmental Medicine and the Soldier Systems Center (ESC-TR-2004-077). Lincoln Laboratory, Massachusetts Institute of Technology.

Smith, D.L., Petruzzello, S.J., Kramer, J.M., & Misner, J.E. (1997). The effects of different thermal environments on the physiological and psychological responses of firefighters to a training drill. *Ergonomics, 40*(4), 500-510.

Soteriades, E.S., Smith, D.L., Tsismenakis, A.J., Bauer, D.M., & Kales, S.N. (2011). Cardiovascular disease in US firefighters: A systematic review. *Cardiology in Review*, *19*(4), 202-215.

Sufi, F., Khalil, I., & Mahmood, A.N. (2011). A clustering based system for instant detection of cardiac abnormalities from compressed ECG. *Expert Systems with Applications*, *38*(5), 4705-4713. doi: http://dx.doi.org/10.1016/j.eswa.2010.08.149

Swart, J., Lindsay, T.R., Lambert, M.L., Brown, J.C., & Noakes, T.D. (2012). Perceptual cues in the regulation of exercise performance – physical sensations of exercise and awareness of effort interact as separate cues. *British Journal of Sports Medicine*, *46*(1), 42-48.

Szinnai, G., Schachinger, H., Arnaud, M.J., Linder, L., & Keller, U. (2005). Effect of water deprivation on cognitive-motor performance in healthy men and women. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, *289*(1), R275-R280. doi: 10.1152/ajpregu.00501.2004

Tucker, R. (2009). The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. *British Journal of Sports Medicine, 43*(6), 392-400. doi: 10.1136/bjsm.2008.050799

United Kingdom Office of the Deputy Prime Minister. (2004). Physiological Assessment of Firefighting, Search and Rescue in the Built Environment (Fire Research Technical Report 2/2005). Retrieved from http://www.firefitsteeringgroup.co.uk/physiologicalassessmentoffirefighting.pdf

United Kingdom Office of the Deputy Prime Minister. (2005). *Operational Physiological Capabilities of Firefighters: Literature Review and Research Recommendations* (Fire Research Technical Report 1/2005).

US Department of Labor. (1999). Chapter 4: Heat Stress. In *Occupational Safety and Health Administration Technical Manual*. Retrieved from https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html

US Food and Drug Administration. (2002). *Guidance for Industry and FDA Staff - Class II Special Controls Guidance Document: Arrhythmia Detector and Alarm*. Retrieved from http://www.fda.gov/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/ucm072671.htm

US Food and Drug Administration. (2013). *Mobile Medical Applications*. Retrieved from http://www.fda.gov/downloads/MedicalDevices/.../UCM263366.pdf

Walsh, J.A., Topol, E.J., & Steinhubl, S.R. (2014). Novel wireless devices for cardiac monitoring. *Circulation, 130*(7), 573-581. doi: 10.1161/circulationaha.114.009024

Weiser, M. (1991). The computer for the 21st century. *Scientific American, 265*(3), 94-104.

Wilkinson, R.T., Herbert, M., & Branton, P. (1973). A portable EEG-sleep recorder of pocket size. In M.H. Chase, W.C. Stein & P.L. Walter (Eds.), *Sleep Research* (Vol. 2, pp. 182 – 192). Los Angeles: Brain Information Service/Brain Research Institute.

Williams-Bell, F., Villar, R., Sharratt, M.T., & Hughson, R.L. (2009). Physiological demands of the firefighter candidate physical ability test. *Medicine and Science in Sports and Exercise, 41*(3), 653-662.

Wood, D.C., & Dadosky, E.J. (2013). Implementing physiological monitoring in the fire service. *Fire Rescue.* Retrieved from http://www.firefighternation.com/article/technology/implementing-physiological-monitoring-fire-service.

Yokota, M., Berglund, L.L.G., Santee, W.R., Buller, M.J., Karis, A.J., Roberts, W.S., Cuddy, J.S., Ruby, B.C., & Hoyt, R.W. (2012). Applications of real-time thermoregulatory models of occupational heat stress: Validation with military and civilian field studies. *Journal of Strength and Conditioning Research, 26*(Supplement 7), S37-S44.

Zephyr Technologies. (2009). *Field testing of FRS 1000 real-time physical status monitoring (PSM) system*. Zephyr Technology Technical Report retrieved from http://zephyranywhere.com/media/WhitePapers/WhitePaper-ZWP-004-FR-Zephyr-Technology-HAZMAT-2009-Aug-20a.pdf

Zou, K.H., O'Malley, J., & Mauri, L. (2007). Receiver-Operating Characteristic Analysis for Evaluating Diagnostic Tests and Predictive Models. *Circulation, 115*(5), 654-657. doi: 10.1161/circulationaha.105.594929

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