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"SENSING DISASTER": THE USE OF WEARABLE SENSOR TECHNOLOGY TO DECREASE FIREFIGHTER LINE-OF-DUTY DEATHS

by

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December 2015

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After more than 30 years of the American fire service averaging over 100 line-of-duty deaths annually, the technology now exists that can reduce the number of firefighter line-of-duty deaths of cardiac origin. Despite the creation of programs designed to improve firefighters' cardiac health and fitness, no reduction has occurred in the number of firefighters suffering fatal cardiac events. While firefighters can suffer heart attacks or cardiac emergencies anywhere, it has been well documented that firefighters working on the fire ground are exposed to significantly increased risk-factors for the development of coronary heart disease, as well as the exacerbation of underlying cardiac problems. As a result, more firefighters experience signs and symptoms of cardiac complications while on the fire ground than anywhere else while on duty.

The development of wearable sensor technology now allows for incident commanders or their assigned designees to monitor the real-time physiologic health and wellness of each and every firefighter operating on the fire scene. Through the use of wearable sensor technology, firefighters can not only have their vital signs and EKG monitored, but this technology will also allow for real-time tracking of their location within a structure and their body motion, speed, and direction of travel.

The use of wearable sensor technology in the fire service will have a significant impact on improving not only firefighter health and safety, but when fully developed, will improve other aspects of the firefighting profession, such as search and rescue and fire attack.

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"SENSING DISASTER": THE USE OF WEARABLE SENSOR TECHNOLOGY TO DECREASE FIREFIGHTER LINE-OF-DUTY DEATHS

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After more than 30 years of the American fire service averaging over 100 line-of-duty deaths annually, the technology now exists that can reduce the number of firefighter line-of-duty deaths of cardiac origin. Despite the creation of programs designed to improve firefighters' cardiac health and fitness, no reduction has occurred in the number of firefighters suffering fatal cardiac events. While firefighters can suffer heart attacks or cardiac emergencies anywhere, it has been well documented that firefighters working on the fire ground are exposed to significantly increased risk-factors for the development of coronary heart disease, as well as the exacerbation of underlying cardiac problems. As a result, more firefighters experience signs and symptoms of cardiac complications while on the fire ground than anywhere else while on duty.

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The use of wearable sensor technology in the fire service will have a significant impact on improving not only firefighter health and safety, but when fully developed, will improve other aspects of the firefighting profession, such as search and rescue and fire attack.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACOEM	American College of Occupational and Environmental Medicine
AHA	American Heart Association
BAN	body area network
BSN	body sensor network
CHD	coronary heart disease
CO	carbon monoxide
CO2	carbon dioxide
COPD	chronic obstructive pulmonary disease
CP	command post
CR	cardiac rehabilitation
CVA	coronary vascular accident
CVD	coronary vascular disease
DARPA	Defense Advanced Research Projects Agency
DOS	denial of service
ECG/EKG	electrocardiogram
ECPA	Electronic Communication Privacy Act
EHS	electronic health records
EMI	electromagnetic interference
EMS	Emergency Medical Services
ePHI	electronic personal health information
EU	European Union
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
FIP	Fair Information Practices
GDP	gross domestic product
GPS	global positioning system
GSM	global system for mobile communications
GTWM	Georgia Tech Wearable Motherboard
HCl	hydrogen chloride
HCN	hydrogen cyanide
HIPAA	Health Insurance Portability and Accountability Act
HITECH	Health Information Technology for Economic and Clinical Health
HR	heart rate
HSPH	Harvard School of Public Health
HUD	heads-up display

IAFC	International Association of Fire Chiefs
IAFF	International Association of Fire Fighters
IC	incident commander
IDLH	immediate danger to life and health
IG	inner garment
IoT	Internet of Things
IPS	indoor positioning system
ISM	Industrial, Scientific and Medical (Band)
IT	information technology
LODD	line of duty death
M2M	machine to machine
MEMS	microelectromechanical systems
MI	myocardial infarction
NFFF	National Fallen Firefighters Foundation
NFPA	National Fire Protection Association
NGO	non-governmental organizations
NIOSH	National Institute for Occupational Safety and Health
NO2	nitrogen dioxide
O2	oxygen
O3	ozone
OG	outer garment
OSHA	Occupational Safety and Health Administration
OT	overtime
PDA	personal digital assistant
PEB	professional electronic box
PHI	protected health information
PSOB	Public Safety Officers’ Benefit
PSOEA	Public Safety Officers’ Education Assistance
REL-ST	recommended exposure level—short term
RIC	rapid intervention crew
ROM	range of motion
RR	respiratory rate
SCD	sudden cardiac death
SpO2	saturation of peripheral oxygen
UPDRS	unified Parkinson’s disease rating scale
USD	United States dollars
UWB	ultra wide band

VTAMN	Vetement de Te'le' Assistance Medicale Nomade
WHO	World Health Organization
WMTS	wireless medical telemetry services
WST	wearable sensor technology

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EXECUTIVE SUMMARY

The purpose of this research was to determine how the fire service could create and implement a policy that leverages the capabilities of wearable sensor technology (WST) to reduce cardiac related firefighter line-of-duty deaths (LODDs). This thesis research used policy analysis methodology to explore the factors that have led to the consideration of using WST in the fire service. The research also analyzed the four leading WST designs that have marketed themselves for use in the fire service comparing their individual capabilities and design features for strengths and weaknesses. The current use of WST in the home health and physical therapy fields has been analyzed to reveal the technological capabilities to record, analyze and transmit critical health data accurately using wireless systems to monitor numerous health conditions. The primary sources of information for this research came from a combination of professional organizational reports, journal articles, conference reports, medical journal articles, prototype design documentation, prototype study reports, and field trial reports.

For the last 30 years, the fire service has experienced over 100 firefighter line-of-duty deaths, with the largest percentage of those deaths being caused by heart disease that result in cardiac arrest. While it is known that firefighters face the same risk factors as every other American for heart disease, firefighters are also exposed to additional risk factors unique to their job. The combination of sympathetic nervous system activation, strenuous physical work, heat stress/dehydration, and environmental conditions has been shown to lead to significant cardiovascular strain. As a result of this additional strain, more firefighters die of cardiac events while operating on the fire ground than during any other aspect of their job. It has become even clearer as the number of structural fires has been steadily declining; however, the number of firefighter deaths at fire grounds has increased. Additionally, it has been demonstrated that the majority of firefighter cardiac events occur between the hours of noon and midnight, which coincides with the highest number of fire incidents. This pattern of cardiac events seen in firefighters is vastly different than those in general public where cardiac events are most likely to take place between 6am and noon.

While all four of the WST designs being marketed for use in the fire service have similar basic capabilities, many additional sensor options and design differences distinguish each system from the others. While the ProeTex, Georgia Tech Wearable Motherboard (GTWM), VTAMN, and MagIC are capable of monitoring the wearers vital signs and EKG, not all are able to transmit the data wirelessly, or monitor the wearers' movements and the environmental conditions around the wearer. Physiologic monitoring will be the most important aspect of WST for the reduction of firefighter LODD, as it permits for the rapid recognition and response to physiologic changes in a wearer's condition. It has been shown in numerous studies that the early recognition of cardiac dysrhythmia through the use of an EKG, and changes in the individual's vital signs, along with the rapid initiation of cardiac care, results in substantially higher rates of survival for heart attack and cardiac arrest in both the short and long term.

While concern exists over the security of personal medical information being wirelessly communicated from the WST garments, through the use of proper encryption and authentication mechanisms, protect data will be protected from theft or misuse.

Based on the research and studies done for this thesis, it is recommended that the American fire service further explore the implementation of the ProeTEX WST garment to reduce firefighter line-of-duty deaths. This technology, once tested and approved by Occupational Safety and Health Administration (OSHA) and National Fire Protection Association (NFPA), should become a mandated piece of equipment that should be required of all American fire departments regardless of career, volunteer, or combination status. The potential benefits of this technology appear to extend beyond the capability to reduce the line-of-duty death benefits outlined in this research, and may extend into many other facets of the fire service.

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I. INTRODUCTION

The fire service has been on the front-line of homeland defense since 1736 when Benjamin Franklin organized the first professional fire department in Philadelphia. With a lack of safety standards, organization and equipment, the death of a firefighter in those early years was not uncommon. Unfortunately, despite the creation of numerous safety standards, clearly established organizational structures, and high-tech equipment, firefighters are still dying in the line-of-duty.

Annually in the United States, over 100 firefighter line-of-duty deaths (LODDs) occur, and the leading cause of death in those firefighters is coronary heart disease (CHD).[1] Firefighters must contend with the same cardiac risk factors that most Americans face, such as hypertension, poor diets, lack of exercise, and stress. What is less known is that firefighters have work-place exposures that increase their risk of CHD that are specific to the firefighting profession.

Although national standards and professional initiatives have been established to decrease the risks associated with firefighting and CHD, little change has been seen in the number of firefighters dying each year in the line-of-duty. A new technology aimed at decreasing the number of LODDs in firefighters is the use of wearable sensor technology (WST). This technology would allow incident commanders (IC) to track the physiological status of firefighters at the scene of emergencies to monitor their health status and ensure they do not operate beyond their established "healthy limits" boundaries. Use of this technology does have its critics who voice concern over personal privacy issues and the protection of personal medical information as they relate to use of WST. Although the use of WST in the fire service has not begun, Europe and the United States already are strongly pushing to create and market the first WST system specific to the fire service.

[1] Stefanos N. Kales et al., "Emergency Duties and Deaths from Heart Disease among Firefighters in the United States," *New England Journal of Medicine* 356, no. 12 (2007): 1207–1215, doi:10.1056/nejmoa 060357.

A. PROBLEM STATEMENT

While many industrial professions have decreased their on-the-job death rates through the creation of new and more stringent safety regulations, the fire service has not seen the same improvement in its LODD statistics despite numerous improvements in safety regulations, equipment, and health standards created by its professional organizations.[2]

Over the last 30 years, it has been shown that the single largest percentage of LODDs for firefighters (45%) comes from heart disease resulting in sudden cardiac arrest.[3] Although structure fires are occurring less frequently in the United States, on duty firefighter deaths are not; almost half of these deaths are now related to cardiovascular events.[4] While little debate has occurred that the primary cause of the cardiac LODDs is the presence of underlying CHD, numerous theories and studies have focused on what makes firefighters more prone to fatal cardiac events than other professional workers.

CHD among firefighters is caused by the combining of personal and work-place risk factors. The personal risk factors firefighters face are shared by most Americans and documented by the American Heart Association (AHA). Not as widely known, however, is that firefighters are exposed to work specific risk factors that are linked to increased cardiovascular disease and death.[5] The combined effects of "sympathetic nervous system activation, prolonged physical work periods, heat stress, dehydration, and extreme environmental conditions" have been shown to create heightened cardiovascular stress.[6] Firefighters encounter these factors repetitively during firefighting operations. The result, therefore, is that the stressors faced by firefighters may work either separately or together

[2] Elise Fisher et al., *Contributing Factors to Firefighter Line-of-Duty Death in the United States* (Washington, DC: International Association of Firefighters, 2006).

[3] Daniel DeNoon, "Firefighter Killer: Heart Disease," *Webmd*, March 21, 2007, http://www.webmd.com/heart-disease/news/20070321/firefighter-killer-heart-disease?

[4] Jorn Olsen and Linda Rosenstock, "Firefighting and Death from Cardiovascular Causes," *New England Journal of Medicine* 356, no. 12 (2007): 1261–1263.

[5] T. Baldwin, T. Hales and S. Jackson, *NIOSH Alert: Preventing Fire Fighter Fatalities Due to Heart Attacks and Other Sudden Cardiovascular Events* (Washington, DC: National Institute for Occupational Safety and Health, 2007).

[6] David Barr, Stefanos Kales, and Dennis Smith, "*Extreme Sacrifice: Sudden Cardiac Death in the U.S. Fire Service,*" *Extreme Physiology and Medicine* 2, no. 6 (2013): 105–133.

resulting in exacerbation of CHD depending on which stressors are faced and the degree to which they are experienced by individual firefighters.[7] While this thesis focuses on firefighter deaths related to CHD, it should be recognized that for every firefighter line-of-duty-death, 17 non-fatal cardiovascular emergencies occur to firefighters operating on the fire ground while performing their duties.[8] In 2013, an estimated 2,200 firefighters experienced a cardiovascular event while on duty that did not result in sudden death.[9]

The National Fire Protection Association (NFPA), along with other professional organizations, has worked to develop programs aimed at countering CHD risks facing firefighters. However, despite programs and standards like *NFPA 1500, Fire Department Occupational Safety and Health Program*, *NFPA 1582, Standard on Comprehensive Occupational Medical Program for Fire Departments, NFPA 1583, Standard on Health-related Fitness Programs for Fire Fighters,* and the International Association of Firefighters and International Association of Fire Chiefs (IAFF/IAFC's) *The Fire Service Joint Labor Management Wellness-Fitness Initiative*, the number of firefighters suffering CHD and related cardiac LODDs has not changed.

The fire service has already begun to look at WST as a potential solution to specific challenges, including the monitoring of firefighter physiological conditions. The first research in this field was done at Georgia Tech University, but was done with a focus on how WST could be used on the battle field for the U.S. military. Recognizing the potential that WST could have in other industrial applications, Georgia Tech continued to perform research into its capabilities. In 2006, a European consortium also began work on a WST; however, this research was focused exclusively on how WST could be used by firefighters and civil protection rescuers. This system, called PROE-Tex, includes not only sensors that monitor the firefighters physiological conditions, but also has capabilities for detecting and alerting the wearer of possible environmental dangers, like the presence of high concentrations of toxic gases. Following the lead of the

[7] Barr, Kales, and Jackson, *Extreme Sacrifice*, 133.

[8] Ibid.

[9] Ibid.

ProeTEX project, other WST systems have gone into development including the MagIC system, and VTAMN system.

This thesis not only explores the potential benefits of WST as a means to decrease the number of cardiac related LODDs in firefighters, but also considers the privacy and legal implications of transmitting personal medical data. An implementation policy will be proposed that outlines the critical issues that must be considered prior to the fire service adoption of WST for its firefighters. This thesis will contribute to a greater understanding of how the use of WST can assist in decreasing firefighter LODDs, while increasing the understanding of personal privacy concerns and the protection of personal medical information as it applies to the use of WST.

B. RESEARCH QUESTION

How can the fire service create and implement a policy that leverages the capabilities of WST to reduce cardiac related firefighter LODDs while also considering the privacy and legal implications of transmitting personal medical data?

C. LITERATURE REVIEW

This literature review examines why the use of WST has been sought after and is being designed, in many cases, for use in the medical and home health fields. It also examines the current body of knowledge on firefighter LODDs, the applications and uses of WST in the medical field, and how WST could be applied in the fire service to reduce LODDs. The discussion associated with this review includes the projections of the increased need for home health monitoring, as well as the financial motivation behind the use of WST in this field. Further, this review includes a discussion on how the change in American culture towards Americans being active participants in their own health care and well-being is opening new markets for WST. The relevant literature identified in this document was primarily published after 2003. The sources have been derived from academic journals, non-governmental organizations (NGOs), government reports, and professional journals.

The shortage of medical professionals along with the increasing demands on the healthcare system in the United States has resulted in a significant burden being placed on the American medical system.[10] With America's aging population and current economic trends a need exists to discover new methods and technologies that can help to lift the burden of medical care off the clinical professional and place it on a new technology that can provide the same or better level of care that the traditional clinical medical professional has done in the past.[11] The use of WST offers solutions to many of the problems and supports trends in modern healthcare needs and societal demands.

Despite the implementation of the Affordable Care Act and the assurance of medical insurance for all, society had recognized that the costs of medical care in the United States has spun out of control and needed to be curtailed without sacrificing the quality of available care. This combination of more affordable medical care that is still of the highest quality and that remains cutting edge can be achieved through the use of new and different technologies that exist outside of the hospital setting for health management and disease intervention. Individual, portable health monitoring systems designed for application outside of the hospital or clinical settings have been used in the past. The Holter monitor, designed to record the wearers' heart activity in the event of an abnormality, is just such a device. However, it is limited in what it can detect and is only able to record data, but not transmit or analyze the data for instantaneous diagnosis. As a result, Holter technology, as the real-time monitoring of patients, is of no benefit.[12] Technology has advanced to the point that has "left the era of data collection and have entered the telemetric age."[13] By definition, telemetry is "the process or practice of obtaining measurements in one place and relaying them for recording or display

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[10] Kenneth Armijo et al., "Wireless Sensor Networks for Home Health Care," in *21st International Conference on Advanced Information Networking and Applications Workshop* (Berkley: University of California, 2015), 832–837.

[11]Ibid.

[12] Andreas Lymberis and Andre Dittmar, "Advanced Wearable Health Systems and Applications—Research and Development Efforts in the European Union," *IEEE Eng. Med. Biol. Mag.* 26, no. 3 (2007): 29–33, doi:10.1109/memb.2007.364926.

[13] Patrick Tucker, *The Naked Future* (New York: Penguin Group, 2014), xv.

to a point in the distance."[14] From its development on the battlefields of the Middle East to its current applications in civilian medicine, the growth and application of telemedicine has resulted in the creation of a new vocabulary. This new technology has introduced terms, such as "e-health," "telehealth," "telecare," "telemonitoring," "telediagnosis," "telerehabilitation," "teletreatment," and "home telecare."[15]

The evolution underway in the healthcare and health delivery systems of the United States and worldwide is motivated by four driving forces: demographic changes, increasing healthcare costs, cultural changes, and scientific progress.

America is experiencing a significant change within its population composition. In addition to an aging population, American society will see the greater integration of those with disabilities and an "increase in chronic diseases will be more and more common in many societies."[16] According to the U.S. Bureau of the Census, "the number of adults age 65–84 is expected to double from 35 million to nearly 70 million by 2025 when the youngest Baby Boomers retire."[17] In addition, the World Health Organization (WHO) lists cardiovascular disease as the cause of 30 percent of all deaths worldwide. That number is expected to rise dramatically with the rapid aging of the population. Another disease that has been directly linked to the acceleration of cardiovascular disease is diabetes. Diabetes has already been diagnosed in more than 180 million people and that number is projected to double in the next 20 years. Finally, the number of people being diagnosed with neuro-degenerative diseases including Parkinson's and Alzheimer's has risen rapidly, which threaten to affect millions more worldwide.

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[14] Ibid.

[15] Andreas Lymberis and Silas Olsson, "Intelligent Biomedical Clothing for Personal Health and Disease Management: State of the Art and Future Vision," *Telemedicine Journal and E-Health* 9, no. 4 (2003): 379–386.

[16] Ibid.

[17] Emil Jovanov, Aleksandar Milenkovic, and Chris Otto, "Wireless Sensor Networks for Personal Health Monitoring: Issues and Implementation," *Computer Communications* 29, no. 13–14 (2006): 2521–2533.

The cost of health care in the United States of $2.9 trillion currently equals an estimated 16% of the nation's gross domestic product (GDP).[18] As hospital costs continue to rise, home health-care through the use of WST is a potential solution to the problem facing the American health care system.[19] Additionally, the ability to recognize and respond to early symptoms of a disease, which is a benefit of a continuous monitoring system, will allow diseases to be treated earlier, before they are able to progress and become more expensive and difficult to cure.[20] One of the important benefits of WST is that it will help control the increasing costs of health care by improving the interaction time between a physician and patient, as well as by allowing for the around-the-clock monitoring of health conditions. Annually, the United States pays an estimated $5.1, $12.4, and $44 billion, respectively to treat asthma, depression and diabetes.[21] An article in *ON World* journal called "WSN for Healthcare" estimated "wireless sensor networks could reduce the annual healthcare costs in the United States by $25 billion."[22]

A cultural shift towards individuals wanting to be more involved and in control of their own health care and health monitoring is also occurring around the globe.[23] People are adopting a "health consciousness" attitude and are eager to assume more responsibility and have a louder voice in the decisions made regarding their own health.[24]

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18 Jason Millman, "Here's Exactly How the United States Spends $29 Trillion on Health Care," *The Washington Post*, 2014.

19 Jovanov, Milenkovic, and Otto, "Wireless Sensor Networks for Personal Health Monitoring," 2521–2533.

20 Sundaresan Jayaraman and Sungmee Park, "Enhancing the Quality of Life through Wearable Technology," *IEEE Engineering in Medicine and Biology Magazine* 22, no. 3 (2003): 41–48, doi:10. 1109/memb.2003.1213625.

21 Lymberis," Intelligent Biomedical Clothing," 379–386.

22 Charlie Chi, Darryl Gurganious, and Mareca Hatler, "Health & Wellness Wireless Sensor Networks," *ON World* 1, no. 1 (2013): 1–81.

23 Jayaraman and Park, "Enhancing the Quality of Life through Wearable Technology," 41–48.

24 Lymberis and Olsson, "Intelligent Biomedical Clothing for Personal Health and Disease Management: State of the Art and Future Vision," 379–386.

Patients are now "health consumers asking for better health and lifestyle management, including nutrition, fitness and sport."[25]

Technological advancements now allow for answers to medical issues built on integrated, intelligent, and cost-effective systems, such as WST.[26] The benefit of rehabilitation comes primarily through the ability to see the effects of medical decisions and interventions on the everyday quality of life of the patient. With WST, that ability can now be realized. WST, with its ability to provide biomedical feedback, allows wearers who suffer from chronic disease to comprehend their daily choices based on immediate feedback, and thus, improve their ability to manage their disease on their own.[27] According to Fabrice Axisa, "the early detection offered by WST, can limit the occurrences of acute events and complications that may lead to hospitalization."[28] This ability to detect abnormal physiological presentations can also decrease the need for prolonged in-patient treatments. For many, rehabilitation will become a permanent part of their lives. It will place new responsibilities on both the patient and their family members to be active supporters and involved partners in the rehabilitation process. For post-event patients, such as those who have suffered a stroke, heart attack, etc., WST systems allow rehabilitation to take place around the clock through continual monitoring, and immediate feedback from the garment. Data received by the monitoring physician can allow for prescriptions to be made, discontinued, or altered with the goal of acquiring the desired affect without having to wait until the next appointment. For those who do not have underlying disease, WST can improve their methods of achieving a healthier self by monitoring their exercise habits and routines while also providing feedback and analysis to assist them in achieving their fitness goals. Finally, According to Ilkka Korhonen, WST will benefit those at greater risk of disease because it "will provide information on how to deal with individual risk factors such as hypertension, obesity, diabetes, physical

[25] Lymberis and Olsson, "Intelligent Biomedical Clothing for Personal Health and Disease Management: State of the Art and Future Vision," 379–386.

[26] Fabrice Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," *IEEE Transactions on Information Technology in Biomedicine* 9, no. 3 (2005): 325–336, doi:10.1109/titb.2005.854505.

[27] Ibid.

[28] Ibid.

inactivity, and stress through personalized training plans, and will provide motivation to change high-risk behavior."[29]

According to Andreas Lymberis, medicine has traditionally focused on treatments that revolve around the use of "drugs, mechanics, prosthesis, and surgery."[30] He went on to document that "More recently, the healthcare community's investments and expectations have shifted towards earlier detection of disease, health status monitoring, healthy lifestyles, and overall quality of life."[31] Those who provide health care are now seeking less expensive methods of providing care that maintain or improve the standard of care but do so without requiring the patient to travel to a clinical or hospital setting. Along with the changes focused on detecting disease earlier, the approach to medicine itself has changed with many in the medical profession adopting the idea of "continuity of care."[32] This "continuity of care" supports the change of focus from "hospital-centered health care" to "patient /citizen centered health" and "cure" to "prevention," and significantly expands the use and potential positive impact use of WST.[33]

1. Definitions

According to Dr. Lori Moore-Merrell, Assistant to the General President of the IAFF, who "is in charge of technical assistance for labor issues, and the Federal Emergency Management Agency (FEMA)," the definition of a LODD is:

> Any injury or illness sustained while on duty that proves fatal. The term "on duty" refers to "being involved in operations at the scene of an emergency, whether it is a fire or non-fire incident, responding to or returning from an incident, performing other officially assigned duties such as training, maintenance, public education, inspection, court

[29] Illka Korhonen, Juha Parkka and Mark Van Gils, "Health Monitoring in the Home of the Future," *IEEE Eng. Med. Biol. Mag.* 22, no. 3 (2003): 66–73, doi:10.1109/memb.2003.1213628.

[30] Lymberis and Andre Dittmar, "Advanced Wearable Health Systems and Applications—Research and Development Efforts in the European Union," 29–33.

[31] Ibid.

[32] Lymberis and Olsson, "Intelligent Biomedical Clothing for Personal Health and Disease Management: State of the Art and Future Vision," 379–386.

[33] Ibid.

testimony, and fundraising, and being on-call, under orders, or on standby duty, except at the individuals home or place of business.[34]

The second important definition to understand is that of a "firefighter." For the purpose of this thesis, the term "firefighter," as it is agreed upon by Dr. Moore-Merrell and FEMA, is defined as:

> All members of organized fire departments with assigned fire suppression duties in all 50 states, the District of Columbia, and the territories of Puerto Rico, the Virgin Islands, American Samoa, the common-wealth of the Northern Mariana Islands, and Guam. It includes all career and volunteer firefighters, full-time public safety officers acting as firefighters; fire police, state, territory and federal government fire service personnel, including wild land firefighters; and privately employed firefighters, including employees of contract fire departments and training members of industrial fire brigades, whether full or part time. It also includes contract personnel working as firefighters or assigned to work in direct support of fire service organizations.[35]

According to their definition:

> Not only local and municipal firefighters but also seasonal and full-time employees of the U.S. Forest Service, the National Park Service, The Bureau of Land Management, the Bureau of Indian Affairs, the U.S. Fish and Wildlife Service, and state wild land agencies. The definition also includes prison inmates serving on fire crews; firefighters employed by other governmental agencies, such as the U.S. Department of Energy; military personnel performing assigned fire suppression activities; and civilian firefighters working at military installations.[36]

Although Dr. Moore-Merrell et al. and FEMA have created these mutually agreed upon definitions of "LODD" and "firefighter," it appears from the literature that those definitions have been adopted by almost all researchers in the field of fire service studies. Their expert perspectives as representatives of fire service governing agencies have satisfied those who may question the presence of bias in their methods and wording during the creation of these definitions. These definitions have also been used by both federal and state governments to establish the definitions of LODD for "presumptive" deaths for reward of death and disability pay.

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[34] Fisher et al., *Contributing Factors to Firefighter Line-of-Duty Death in the United States.*

[35] Ibid.

[36] Ibid.

2. Coronary Heart Disease in Firefighters

Many people incorrectly assume that a firefighter's greatest threat of death while at work comes directly from fires or building collapse. However, Daniel DeNoon, senior medical writer for *WebMd*, Kevin Spratlin, author for *Fire Engineering Magazine*, and Dr. Stefanos Kales, the Director of Occupational and Environmental Residency at Harvard School of Public Health (HSPH), have all been able to demonstrate and document that over the last 30 years, the single largest percentage of LODDs for firefighters, 45%, came from heart disease resulting in sudden cardiac arrest.[37] As FEMA documented in their report of firefighter deaths in 2013, 106 firefighters died in the line-of-duty, which was an increase of 24 firefighters from the previous year's total.[38]

3. Causes of Coronary Heart Disease in Firefighters

While little debate occurs in the literature that underlying CHD is the primary cause of the cardiac LODDs, numerous different theories and studies have focused on what makes firefighters statistically more prone to fatal cardiac events and cardiac arrest than other professions. Dr. Kales' research found that the majority of on duty deaths in firefighters of cardiac origin stemmed from the firefighters underlying CHD;[39] however, Dr. T. S. Hales, a member of the NFPA Technical Committee on Occupational Safety and Health, and Vice Chair of the Public Safety Medicine Section of the American College of Occupational and Environmental Medicine (ACOEM), along with Dr. Kales, David Barr, a physician and professor of Health and Exercise Sciences at Skidmore College, and Denis Smith, a professor at the University of Illinois, went on to state that firefighter CHD is due to a combination of both off-duty and workplace factors.[40] These

[37] DeNoon, "Firefighter Killer: Heart Disease"; David Christiani et al., "Firefighters and On-Duty Deaths from Coronary Heart Disease: A Case Control Study," *Environmental Health* 2, no. 1 (2003): 14; Kimberly Quiros, "Firefighter Obesity: A Public Safety Risk," Healthy-Firefighter.Org, 2015, http://www.healthy-firefighter.org/media-room/524-firefighter-obesity-a-public-safety-risk; David Christiani et al., "Emergency Duties and Deaths from Heart Disease among Firefighters in the United States," *New England Journal of Medicine* 356, no. 12 (2007): 1207–1215.

[38] United States Fire Administration, *Firefighter Fatalities in the United States in 2013* (Emmitsburg, MD: FEMA, 2014).

[39] Christiani et al., "Firefighters and On-Duty Deaths from Coronary Heart Disease: A Case Control Study," 1–14.

[40] Barr, Kales, and Jackson, *Extreme Sacrifice*, 133.

workplace factors include strenuous physical activity, heat stress/dehydration, environmental conditions, and prolonged sympathetic nervous system activation due to various psychological and sensory system assaults. In addition, Dr. Kales and Dr. Linda Rosenstock, who served as the Director of the National Institute for Occupational Safety and Health, pointed out that very few fire departments, despite a NFPA recommendation to do so, require veteran firefighters to continue to keep the physical fitness standards they had to display to be hired. As a result, many experienced firefighters are unable to meet the minimum exercise standards necessary to perform many of the demanding tasks required on the fire ground.[41]

No disagreement appears in the literature about the risks associated with firefighting or the workplace factors that add to the causes of firefighter LODDs. Dr. Kales, in his research for the *New England Journal of Medicine* claimed that firefighters were found to be "12–136 times more likely to die of heart disease when putting out a fire; 3 to 14 times more likely to die of heart disease while responding to an alarm; 2 to 10.5 times more likely to die of heart disease while returning from an alarm; and 3 to 7 times more likely to die of heart disease while training when compared to performing non-emergency duties."[42] Further solidifying the concept that firefighters who suffer cardiac events often have those events triggered by firefighting duties, Dr. Stefanos Kales found that the majority of firefighter cardiac events occur between the hours of noon and midnight, which coincides with the highest number of fire incidents.[43] This circadian rhythm of cardiac events demonstrated by firefighters is vastly different from those of the public, where the cardiac events are most likely to take place between 6am and noon.[44]

[41] Olsen, *Firefighting and Death, 1261–1263.*

[42] Kales et al., "Emergency Duties and Deaths from Heart Disease among Firefighters in the United States," 1207–1215.

[43] Ibid.

[44] Kales et al., "Emergency Duties and Deaths from Heart Disease among Firefighters in the United States," 1207–1215.

4. Wearable Sensor Technology in the Medical Field

Chris Baker, who specializes in Distributed Computing and Computer Communications at the University of California—Berkeley, speaking at the 21st International Conference on Advanced Information Networking and Applications Workshops, in 2007, pointed out that in recent years, the United States has spent $2 trillion per year on health care. That number equals nearly 16% of the GDP.[45] He went on to state that those health care costs are expected to rise as data indicates that the U.S. population in the "over 60" population is projected to increase by 25% by the year 2030.[46]

The development of WST may provide an answer to this expected demand on the nation's medical system. WST may keep many people in need of medical observation out of the hospital without compromising their level of care. WST is currently being used to monitor cardiac patients, diabetic patients, cerebral vascular accident (CVA or stroke) patients, and many more individuals who require constant medical monitoring. One of the most common applications in the medical community is to track and monitor the rehabilitation efforts of those recovering from serious medical events, such as CVA and myocardial infarction (MI or heart attack). As stated in a research article on WST by Geng Wu, professor of electrical and computer engineering at the University of Utah:

> One of the primary services is remote patient monitoring and care, wherein a patient wears bio-sensors to record health and fitness indicators such as blood pressure, body temperature, heart rate, and weight. These sensors forward their collected data to a machine-to-machine (M2M) device (e.g., a patient's cell phone) that acts as an information aggregator and forwards the data by sending alerts and appropriate medical records to medical providers.[47]

Shyamel Patel, a specialist in bioinformatics and computational biology, who is working on real-time and embedded systems at Harvard, and agreed with Wu. Patel wrote, "Wearable sensors have diagnostic, as well as monitoring applications. Their

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[45] Armijo et al., "Wireless Sensor Networks For Home Health Care," 832–837.

[46] Ibid.

[47] N. Himayat et al., "M2M: From Mobile to Embedded Internet," *IEEE Communications Magazine* 49, no. 4 (2011): 36–43.

current capabilities include physiological and biochemical sensing, as well as motion sensing. Wireless communication is relied upon to transmit patient's data to a mobile phone or access point and relay the information to a remote center via the Internet."[48]

According to Paul Fergus, Kashif Kifayut, Simon Cooper, and Madjid Merabti, professors of health informatics and artificial intelligence at John Moores University in Liverpool, improvements in sensor nodes now include capabilities for data processing, as well as communication with different sensors within the system. It is now common for sensor nodes to be able to deliver multiple sensing capabilities while still having limited power supplies, operating on low bandwidth, having small memory capability and demanding very little energy. This technology allows for increased duration for continuous health monitoring of an ambulatory patient to provide instant feedback to the system monitors while not being obtrusive for the wearer.[49] Geng Wu stated that most of the WST systems in use today include telemedicine capabilities aimed at "improving patient care by virtue of more accurate and faster reporting of changes in the patients' physical condition, automated connectivity of medical devices to the hospital network and remote management of these devices, and electronic representation and exchange of medical data between hospitals and medical groups."[50] These capabilities are precisely what will be needed on the fire ground to recognize and render immediate medical care to any firefighter who begins to demonstrate signs of operating outside of safe physiological limits, as determined through cardiac dysrhythmia, hypertension, tachycardia or bradycardia, or other physiological limits.

5. Wearable Sensor Technology in the Fire Service

The creators of WST have already recognized the potential benefits of this technology for use in the fire service. Sungmee Park and Sundaresan Jayaraman documented the 1996 research at Georgia Tech University, which was performed through

[48] Maulin Patel and Jianfeng Wang, "Applications, Challenges, and Prospective in Emerging Body Area Networking Technologies," *IEEE Wireless Communications* 17, no. 1 (2010): 80–88.

[49] Simon Cooper et al., "A Framework for Physical Health Improvement Using Wireless Sensor Networks And Gaming," in *3rd International Conference On Pervasive Computing Technologies for Healthcare*, 2009, 1–4.

[50] Himayat, "M2M," 36–43.

a contract with the Department of the Navy, and was funded by the Defense Advanced Research Projects Agency (DARPA). The results of the work performed by Georgia Tech was the creation of the "world's first wearable motherboard, or 'intelligent' garment for the 21st century."[51] Although its original design was for the military, the concept was recognized for its potential applicability in other professions. Davide Curone, the head research engineer for European FP6 Integrated project ProeTEX and European FP7 Project Galileo for Gravity, and Shyamal Patel have both documented the 2006 European-integration project ProeTEX, which began as a combined effort by 23 European Union (EU) countries.[52] According to Curone, the ProeTEX project was "focused on the design of a set of functional 'smart' protective garments incorporating sensors, communication, processing, and power management devices, directly integrated textiles specifically designed for emergency/disaster intervention personnel such as firefighters and civil protection rescuers."[53]

A third WST system continues to grow out of the original work done at Georgia Tech. According to Sungmee Park and Sundaresan Jayaraman, the wearable motherboard concept is still being used with "plug-and-play" sensors that allow various sensors to be attached or removed from the garment as desired by the user.[54] Beyond the ability to collect physiological data about the wearer, the systems currently in design for use by the fire service include many features not seen in the WST used in the medical community. Davide Curone writes about the ability of ProeTex to alert the wearer and the supervisor outside the hazard area if the wearer walks into an area with a high concentration of toxic gases. The alerts would be both an audible and visual alarm to the supervisor and the wearer to notify them of the hazard area that has been discovered.[55] Other capabilities include the ability to monitor for episodes of wearer immobility and/or falls through the means of two triaxil accelerometer modules.

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[51] Jayaraman and Park, "Enhancing the Quality of Life through Wearable Technology," 41–48.

[52] Davide Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," *IEEE Transactions on Information Technology in Biomedicine* 14, no. 3 (2010): 694–701.

[53] Ibid.

[54] Jayaraman and Park, "Enhancing the Quality of Life through Wearable Technology," 41–48.

[55] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

D. RESEARCH DESIGN

This thesis uses policy analysis methodology that explores the factors that have led to the consideration of using WST in the fire service to decrease firefighter LODDs. It also analyzes the four leading WST designs that have been marketed for use in the fire service. The use of WST in home health and physical therapy applications has revealed the technological capabilities of WST to record, analyze and transmit critical health data accurately using wireless systems to monitor numerous health conditions. By analyzing the medical conditions for which WST is currently being used in the home health and physical therapy fields, as well as what WST limitations have been discovered within those fields of medicine, this thesis will project what uses WST may have within the fire service for reducing firefighter cardiac deaths.

This thesis is based on a combination of professional organization study reports, journal articles, conference reports, medical journal articles, prototype design documentation, prototype study reports and field trial reports. Due to the proprietary concerns expressed by the various wearable system designers, it is impossible to conduct independent tests and trials of the technology for this thesis. As a result, this thesis utilizes published research reports, and field trials, as well as user reviews to create comparison points from which to draw conclusions. The variables measured, assessed, and analyzed include communication limitations, sensor adaptability, environmental limitations, range of motions issues, and wearability considerations. Although each of the WSTs might have its own considerations of what they consider to be strengths or weaknesses of their specific system, this research assesses the individual systems for comparison points based on the individual technologies specific to fire service strengths and weaknesses. Additionally, as WST is a new technology, limited real-world application of its usage is available from which to collect data. Thus, the majority of the information available has come from journal articles and conference reports from those who have been working closely with WST as it has developed. Medical journals and professional organization studies are the primary sources for information related to causes of and potential solutions to firefighter LODDs.

While researchers have suggested that WST could be used to monitor firefighter's activity when not on duty or to track their fitness levels beyond the fire scene, this thesis maintains its focus within the boundaries of cardiac related LODD. The use of WST by firefighters when not on duty was not explored since, like firefighter bunker gear, the WST garment will be kept at the fire stations when the firefighter is off-duty due to the possibility of its contamination from exposure to chemicals and carcinogens at fire scenes. In addition, the WST garments themselves would be the private property of the respective department, and thus, not be available for private use by the firefighters when not on duty.

This research also does not discuss the possibility of using WST by the fire service to monitor compliance with physician recommended treatments and medications. To monitor a firefighter's compliance with physician recommended treatments or medications would be a violation of federal laws outlined in 45 CFR parts 160, 162 and 164, which cover the Transactions and Code Set Standards, Identifier Standards, Privacy Rule, Security Rule, Enforcement Rule, and Breach Notification Rule.[56] Each of these laws exists specifically to protect a worker's right to medical information privacy. Although WST developers have suggested these options as benefits of WST to prevent the research from becoming too broad, these uses were not explored.

This thesis includes qualitative analysis to identify the strengths and weaknesses of WST. The components assessed as strengths or weaknesses will include several system capabilities. The first capability is system performance metrics and includes battery life, ease of use, plug and play capabilities and biomechanical efficiency. The second is system functionality issues, which include the ability to monitor vital signs and perform electrocardiograms (EKGs), as well as communicate with external devices. The third component is the maintainability of the system. In this section, the launderability, upgrade capabilities, and battery recharging capability has been assessed. Fourth are the durability concerns of the systems. Considerations, such as flexural endurance, tear resistance, abrasion resistance, heat tolerances, and moisture resistance, have been

[56] "Combined Regulation Text of All Rules," 2015, http://www.hhs.gov/ocr/privacy/hipaa/administrative/combined/index.html.

analyzed. The final components of the systems strength and weakness assessment are the wearability concerns. Considerations, such as the systems weight, ease of body access with the garment in place, range-of-motion (ROM) limitations, and ease to don and doff the system have been assessed.

A separate potential threat to the use of WST is the possibility for invasions of and misuse of personal data, as well as the potential for disciplinary actions for firefighters based on the revelation of poor physical fitness or underlying medical conditions revealed by the use of WST. Using qualitative research methods, the Health Insurance Portability and Accountability Act (HIPAA) has been researched.

The Georgia Tech Wearable Motherboard (GTWM), ProeTEX system, MagIC system and VTAMN system, each of which is a platform for fire service specific WST that are developed or in development, have been analyzed. The general characteristics of each design have been published to allow for a review of their various strengths and weaknesses. These systems have been analyzed based on the study of each system's specific design documentation, prototype study reports, and field trial reports. Since it is not possible to acquire prototypes of these systems for testing, it has been necessary to rely on the testing documentation available from the development teams for this research. This thesis demonstrates a number of scenarios in which WST can be implemented in the fire service.

The outcome of this research yields a conceptual policy model for the use of WST in the fire service, and details a progressive approach to the concerns of personal privacy protection and medical information protection for those who use this technology.

E. UPCOMING CHAPTERS

Chapter II explores the current state of WST by focusing on its various strengths and weaknesses. This chapter also details how WST is currently being used in the home health care field and the benefits and limitations associated with that particular application. The weaknesses of WST discussed include the technological limitations and the wearer limitations of this technology. Chapter III presents analysis of the four leading WST systems that exist today that have marketed themselves as being capable of use by the fire service. Chapter IV details the uses of WST in the fire service along with scenarios that illustrate the real world potential for WST on the fire ground. Chapter IV also details the challenges and concerns that those in decision-making processes may have to consider prior to the implementation of a WST system within their fire department, which includes privacy and security concerns, as well as HIPAA and labor union considerations. Chapter V is the concluding chapter and is the author’s final assessment and determination regarding the use of WST in the fire service, as well as future recommendations. A list of unknowns and limitations of WST is the final component prior to the listing of future research for the use of WST.

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II. CURRENT STATE OF WEARABLE SENSOR TECHNOLOGY

WST has changed dramatically over the few years since its realization. As the miniaturization of sensors has occurred, and power demands have decreased, the range of capabilities and scope of information recovery and communication has grown.[57] The WST of the year 2000 has made been made obsolete by the WST of 2015. The most modern versions of WST have many strengths, such as disease treatment, medical rehabilitation, and the assessment of pharmacological effects for the treatment of chronic medical conditions. In addition, modern WST has advanced communication capabilities that allow for the transmission of data to be carried to distant locations. However, despite the strengths, WST still has weaknesses and areas that need to be addressed.

A. STRENGTHS OF WEARABLE SENSOR TECHNOLOGY

While the ability to see a patient in the clinical setting has proven value, it has become increasingly difficult for physicians to complete a thorough evaluation due the time constraints placed on them by tightly scheduled appointments, and the demands of an overburdened healthcare system.[58] As a result, questions have begun to arise as to whether assessments performed within this setting are accurate enough to allow for accurate diagnoses made in a physician's office that will affect the everyday life of the patient through medications therapy, etc. The use of WST for individuals being treated through rehabilitation presents an ideal application for the technology because of its ability to record quantitative data while patients go through their normal routine both at home and in the community.[59]

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[57] Paolo Bonato et al., "A Review of Wearable Sensors and Systems with Application in Rehabilitation," *Journal of NeuroEngineering and Rehabilitation* 9, no. 21 (2012): 1–16.

[58] Robert Miller and Ida Smith, "Physicians," Use of Electronic Medical Records: Barriers and Solutions," *Health Affairs* 23, no. 2 (2004): 116–126.

[59] Paolo Bonato, "Advances in Wearable Technology and Applications in Physical Medicine and Rehabilitation," *Journal of Nureoengineering and Rehabilitation* 2, no. 1 (2005): 2–19.

1. Successful Applications of Wearable Sensor Technology in the Medical/Home Health Communities

The desire for a wearable sensor system concept originated from the need to monitor patients over extended periods of time. Physicians wanted to monitor their patients whose chronic conditions included risks of acute events or those for whom treatments needed to be assessed in the out-of-hospital environment. A number of uses for WST in rehabilitation or physical medicines have emerged in the past few years. They include simple monitoring of a wearer's daily activity, to disease prevention and the making of medical diagnoses.[60] Integration of sensors into wearable garments can improve at-home healthcare and disease prevention.[61] In the new field of "citizen medicine," the solutions are put in place through the use of WST to allow the patients or their family to be responsible for their own healthcare in their home or wherever they may travel. The objective of this system is to improve a patient's quality of life and the efficiency of healthcare and illness prevention. For those who suffer from chronic medical conditions, WST can assist in monitoring rehabilitation for acute events, tracking disease progression, and observing treatment effectiveness.[62]

WST has had an immediate impact in the field of CR by improving effectiveness, participation, and reducing costs related to post hospitalization care and rehabilitation.[63] In the United States, as it is in the rest of the world, cardiovascular disease (CVD) continues to be the leading cause of death.[64] The direct cost of CVD in the United States is projected to increase from $656 billion in 2015 to over $1.2 trillion by 2030.[65] These

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[60] Q. Cao et al., "Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges," in *High Confidence Medical Device Software and Systems Workshop* (Charlottesville, VA: University of Virginia, 2005).

[61] Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

[62] Ibid.

[63] Alexandros Pantelopoulos and Nikolaos G. Bourbakis, "A Survey on Wearable Sensor-based Systems for Health Monitoring and Prognosis," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 40, no. 1 (2010): 1–12, doi:10.1109/tsmcc.2009.2032660.

[64] Mourad Adnane et al., "Detecting Specific Health-Related Events Using an Integrated Sensor System for Vital Sign Monitoring," *Sensors* 9, no. 9 (2009): 6897–6912, doi:10.3390/s90906897.

[65] Arif Ahsan et al., "Wearable Sensor for Cardiac Rehabilitation," *Insights in Engineering Leadership White Paper* 6, no. 2 (2014): 3–18.

costs are, in part, caused by the fact that prior to the implementation of WST for CR, outpatient CR required patients to make one or more weekly visits to their cardiologist or rehabilitation center for weeks or even months of follow-up care.[66] For those who live significant distances from their doctor or rehabilitation center, these visits often made CR impossible or at least minimized the effectiveness of the treatment. As a result, many did not comply with, or complete their CR, which has demonstrated significant increases in the number of patients who suffer additional MIs and/or other cardiac events.[67]

Before the adoption of WST for CR, participation in CR programs was less than 30% for those patients eligible to participate.[68] Today, patients in need of CR who have access to the WST go through a 2-phase process. Phase 1 takes place while they are still in the hospital following their emergency treatment or diagnosis. During this phase, patients are trained and supervised in the use of the required sensors and in data collection procedures prior to their transition to the outpatient phase, or phase 2.[69] In this phase, an initial 30-day trial occurs during which the patients would be required to visit the rehabilitation center on multiple occasions. This phase of recovery is the most unstable during which it is likely to experience follow-up cardiac events.[70] After the 30-day trial period, visits to the rehabilitation center or physician would become far less frequent or not necessary at all.

Like coronary vascular disease, chronic obstructive pulmonary disease (COPD) is a common medical condition in the United States, and a major health concern. The total costs associated with this disease because of the disability, hospitalizations, and medication costs are estimated to be more than “$15 billion dollars in lost revenues and

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[66] P. A. Ades et al., “Predictors of Cardiac Rehabilitation Participation in Older Cardiac Patients,” *Journal of Cardiopulmonary Rehabilitation* 13, no. 3 (1993): 212–213, doi:10.1097/00008483-199305000-00012.

[67] Ibid.

[68] Ahsan et al., “Wearable Sensor for Cardiac Rehabilitation,” 3–18.

[69] Shyamal Patel et al., “A Review of Wearable Sensors and Systems with Application in Rehabilitation,” *Journal of Neuroengineering and Rehabilitation* 9, no. 1 (2012): 21, doi:10.1186/1743-0003-9-21.

[70] Ibid.

health care expenditures annually."[71] This single disease expense is estimated to account for 16% of the national health care budget.[72] Even as the number of people with COPD increases in the United States, the advancements of the healthcare industry and clinical researchers have done little to improve their ability to monitor these patients through the diseases progression. For many years, COPD patients' conditions were monitored by using a forced expiratory volume test that was thought to be the "gold standard."[73] However, that test, which could only be done in a medical facility, has now been shown to have very little correlation with other treatment measures for COPD, and has never been shown to predict resource utilization or mortality with accuracy.[74] Using WST, patients with COPD are now being monitored through their motor activities. It has been found that the measurement of on-going physical activity in those wearing WST garments while in their homes or out in their communities, combined with physiological data reports, can be used to improve the clinical assessments made for those who suffer with COPD.[75] These combined assessment tools allow for the improved tracking of disease progression and treatments for these patients.

Numerous chronic diseases require medications to be administered over very specific time frames. The ability of users to self-administer these medications as prescribed by dose and time is a significant problem and leads to medication errors.[76] These errors represent the eighth leading cause of death in the United States. This number

[71] Paolo Bonato, "Advances in Wearable Technology for Rehabilitation," *Harvard-MIT Division of Health Science and Technology*, 2009, 145–159.

[72] E. B. Devine, K. So and Leslie Wilson, "Direct Medical Costs of Chronic Obstructive Pulmonary Disease; Chronic Bronchitis and Emphysema," *Respiratory Medicine* 94, no. 3 (2000): 204–213.

[73] Bartolome R. Celli et al., "Standards for the Diagnosis and Treatment of Patients with COPD: A Summary of the ATS/ERS Position Paper," *European Respiratory Journal* 23, no. 6 (2004): 932–946, doi:10.1183/09031936.04.00014304.

[74] Ibid.

[75] Paolo Bonato, "Clinical Applications of Wearable Technology," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (Boston: Harvard University, 2009), 6580–6583.

[76] S. L. Maddigan et al., "Predictors of Older Adults," Capacity for Medication Management in a Self-Medication Program: A Retrospective Chart Review," *Journal of Aging and Health* 15, no. 2 (2003): 332–352, doi:10.1177/0898264303251893.

equals a total that is “more than motor vehicle accidents, breast cancer, or AIDS.”[77] Parkinson’s disease is just one such disease that requires the timely administering of medications that has seen benefits from the use of WST. Traditional treatment of Parkinson’s disease was focused on the replacement of Dopamine, whose deficiency is the primary cause of the symptoms related to the disease.[78] This treatment plan often was successful for a short period in reducing the abnormal muscular tremors, but most patients would eventually develop motor complications related to the treatment. The primary complication was known as “wearing off,” which was the sudden loss of effect as the dosing period concluded that resulted in dyskinesias, which is an uncontrollable twisting of the body as the muscles flex and contort the body in often painful and violent ways.[79] “Wearing off” and dyskinesias create significant physical restrictions for patients, and often can be a barrier to receiving proper treatment for their condition.

Prior to WST, very few tools were available for monitoring and managing motor fluctuations in these patients. In the clinical setting, details and specifics about motor fluctuations were traditionally known by asking the patients to recount how long they felt they had not been benefitting from the treatment. They were asked to recount not just the duration, but also the severity of their symptoms. This retrospective assessment was formalized in subscale four of the unified Parkinson’s disease rating scale (UPDRS).[80] This reporting methodology was clearly susceptible to perceptual bias and recall bias that resulted in a questionable validity of the data it produced, which would be the basis for the ongoing medical care of that patient.

A technique with only slightly better results was the use of patient diaries. In these diaries, the patients would record their symptoms as they occurred. Although the

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[77] Lymberis and Dittmar, “Advanced Wearable Health Systems and Applications—Research and Development Efforts in the European Union,” 29–33.

[78] James Fallon et al., “Systems and Methods Employing Remote Data Gathering and Monitoring for Diagnosing, Staging, and Treatment of Parkinson’s Disease, Movement and Neurological Disorders and Chronic Pain,” *United States Patent and Trademark Office* (2009): 32–67.

[79] K. Ray Chaudhuri and Anthony H. V. Schapira, “Non-Motor Symptoms of Parkinson’s Disease: Dopaminergic Pathophysiology and Treatment,” *The Lancet Neurology* 8, no. 5 (2009): 464–474, doi:10.1016/s1474-4422(09)70068-7.

[80] Ibid.

documentation of these incidents was more accurate, it did not capture many of the other features, such as the severity of the dyskinesias, which body parts were affected, and the duration of effects needed for clinical decision making. In addition, many Parkinson's patients complained that trying to keep an accurate diary was an additional burden they struggled to perform.[81]

The use of WST in the treatment of Parkinson's is based on the immediacy and accuracy of the information regarding the time, duration, frequency, and severity of dyskinesias related to medication "wear off."[82] The combined data acquired by the sensors allows the physicians to document the physiological movements with a degree of reliability that has never before been possible through the use of diaries, patient recall, or even the use of accelerometers. The ability to observe "wear off" gives the physician the ability to alter the medication dosage, time, and frequency that could decrease the symptoms and improve the patients comfort, abilities, and quality of life.[83] The knowledge that WST provides an opportunity for observing body movements opened it up to being useful in the clinical setting for the study of movements by patients while they performed their daily functional tasks. The two applications in which WST has been utilized have been in the treatment of Parkinson's disease and in post-stroke individuals.

Each year, more than 700,000 Americans are affected by CVA in the United States.[84] Better known as strokes, CVAs can affect a person's ability to function due to loss of fine or gross motor control. The recovery process following a CVA is long and continues beyond the hospital stay. Rehabilitation following a CVA can require daily visits to a rehabilitation center for months to years following the event. In rehabilitation, the process is dictated by what is observed in the clinical setting through assessments of the patients' motor abilities, with the expectation that they will improve over time as a result of the rehabilitative care. WST has allowed rehabilitation to extend beyond the

81 Fallon et al., "Staging, and Treatment of Parkinson's Disease," 32–67.

82 Bonato, "Clinical Applications of Wearable Technology," 6580–6583.

83 Fallon et al., "Staging, and Treatment of Parkinson's Disease," 32–67.

84 Judith Mackay et al., *The Atlas of Heart Disease and Stroke* (Geneva: World Health Organization, 2004).

medical facility therapeutic reach and testing capabilities to levels beyond what can be achieved in the clinical setting alone.[85] Since accurate assessments of the patients motor abilities are an important diagnostic tool for choosing the best treatment plans for post-CVA rehabilitation, the ability to record the patients' daily motor abilities accurately is a critical capability. These motor assessments are grounded on the observations of the wearer's motor functions that are based on a set of standardized clinical rating scales.[86] WST is being used to measure and record accurate accounts of the patients' motor abilities in the out of hospital settings and is then used to guide and assess the rehabilitation process.

2. Current Technological Demands of WST in the Medical/Home Health Communities

Technological advancements have allowed for the development of information infrastructures that have been woven into garments that allow the wearers to go about their daily lives unimpeded by the garments presence. The garment, and its technology, allow for the processing, storage, and communication of collected data about the wearers and their activities, as well as the environment in which the wearers find themselves.[87] Current wearable medical systems include an array of different components, such as sensors, wearable materials, "smart textiles," actuators, power supplies, wireless communication modules, control and processing units, interfaces for the wearer, software, and algorithms that allow for data retrieval.[88]

For the use of WST to be beneficial in the medical and home health fields, real-time data acquisition, effective communications, and rapid, accurate processing of data must occur.[89] In addition, event ordering, time-stamping, and synchronization will be needed for useful data processing to take place. The system sensors and other devices

[85] Patel et al., "A Review of Wearable Sensors and Systems with Application in Rehabilitation," 21.

[86] Mackay et al., "*The Atlas of Heart Disease and Stroke*.

[87] Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

[88] Cao et al., "Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges."

[89] Cao et al., "Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges."

must also be able to function with enough reliability to provide "high-confidence" data that can be used for the diagnosis and treatment of medical conditions. Since very few, if any, of the networks needed to support these systems will receive consistent maintenance, the components and devices must be robust in their design.

Although the creation of WST has required much technological advancement, the ability to manufacture and create microelectromechanical systems (MEMS) stands out as the most significant advancement.[90] It has allowed for the miniaturization of sensors; a critical step in the development of WST. These wearable sensors, when linked into sensor nodes, have diagnostic capabilities, as well as patient monitoring applications.[91] Currently, these sensors have capabilities that include physiological monitoring, as well as motion sensing. Sensor nodes provide properties for sensing environments, data processing, and communications with other sensors. They are generally only limited by their battery life span, low bandwidth, memory sizes limitations, and energy usage.[92] The beneficial capabilities can allow for long duration health monitoring while being unobtrusive to the wearer by allowing immediate feedback to the user, as well as medical providers. The biosensors available for use within WST are designed to allow for the measuring of numerous physiological measures, such as "heart rate, blood pressure, body and skin temperature, oxygen saturation, respiratory rate, as well as monitor the patients' electrocardiogram (EKG)."[93] Activity sensors allow the wearable sensor garment, via an algorithm, to determine the wearers' anatomical position to allow the observer to determine and report whether the wearer is prone or supine, moving in either a walk or run, and is even able to determine if they are going up/down stairs with very high accuracy.[94]

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[90] Patel et al., "A Review of Wearable Sensors and Systems with Application in Rehabilitation," 21.

[91] Patel et al., "Wearable Sensors and Systems with Application in Rehabilitation," 1–16.

[92] Danilo DeRossi et al., "Knitted Bioclothes for Cardiopulmonary Monitoring," in *25th Annual International Conference of the IEEE Engineering In Medicine And Biology Society* (Boston: Harvard, 2003), 3720–3723.

[93] Jayaraman and Park, "Enhancing the Quality of Life through Wearable Technology," 41–48.

[94] Jayaraman and Park, "Enhancing the Quality of Life through Wearable Technology," 41–48.

Using a process known as machine-to-machine (M2M) communications, the sensors contained within the WST forward the data they have collected to a M2M device such as the patient's cell phone, which functions as a data collector and transmits the information forward to the appropriate medical providers.[95] In emergency situations, an M2M device can even notify Emergency Medical Services (EMS) of any acute and critical changes in the patient's physiologic status that may prompt an EMS response. The M2M device can also send the patients current medical condition to the hospital physicians while still enroute to the facility.

The transmission of data can be performed by either a collection of wireless links or via a wired in system. While wires offer some benefits, wearer comfort issues, as well as increased risk of system failure related to their use, can result. Wireless links allow for the formation of body area networks (BAN) or body sensor network (BSN).[96] The most commonly used wireless communication standards in BANs are IEEE 802.15.1 (Bluetooth) and 802.15.4 (Zigbee).[97] With the development of these standards, tethered communication systems are becoming obsolete. The recent development of the IEEE 802.15.4a standard is based on ultra-wide-band (UWB) impulse radio that will allow for low-powered operations and lower-cost, but require "high data rate sensor network applications," which could provide more accurate wearer location approximations.[98] Due to the heterogeneity that exists in many of the medical and home health WST applications, communications between multiple sensors or devices may occur on multiple bands using different protocols. Implanted medical devices, such as pace-makers and internal defibrillators, are permitted to use a licensed band designated for that purpose specifically by the Federal Communications Commission (FCC).[99] Thus, to prevent interference on the overcrowded and unlicensed industrial, scientific and medical (ISM)

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95 Himayat, "M2M," 36–43.

96 Egidio Astesiano et al., *Banip: Enabling Remote Healthcare Monitoring with Body Area Networks* (Berlin: Springer Berlin Heidelberg, 2004).

97 Annalisa Bonfiglio et al., "Smart Garments for Safety Improvement of Emergency/Disaster Operators," in *29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2007, 3962–3965.

98 Patel et al., "Wearable Sensors and Systems with Application in Rehabilitation," 1–16.

99 Patel et al., "Wearable Sensors and Systems with Application in Rehabilitation," 1–16.

band, some WST systems are using the wireless medical telemetry services (WMTS) band at 608MHz.[100]

B. WEAKNESS'S OF WEARABLE SENSOR TECHNOLOGY

WST had long been possible only in the world of Star Trek. However, as technology and computer capabilities improved, the concept transitioned from "someday" to "today." Despite the significant strides that have been made towards the realization of WST, a number of limitations still exist to its use. Primary are the technological limitations and wearer concerns. These issues are both discussed in the upcoming sections.

1. Technological Limitations

Although WST has been conceptualized for many years, it has not been until recently that the technology has developed and sensors have been miniaturized sufficiently to allow for its realization. The result of this recent technological construction is the fact that many weaknesses in the technology still need to be improved for WST to meet the high expectations that many have placed on it. Before WST can be implemented on a large scale, numerous hurdles must be overcome. These hurdles include technological barriers, such as communication limitations, sensor limitations, and a lack of available battery technology.[101] Also, non-technology issues, such as wearer limitations and cultural barriers, may inhibit the successful use of this technology.

2. Communication Limitations

In a single node system with its own energy source, communication is generally a very simple process of data acquisition and transmission. However, with the complexity inherent in the muli-nodal network systems that comprise WST, communication becomes

[100] Cao et al., "Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges."

[101] Himayat, "M2M," 36–43.

a much more complex issue. One of the critical demands of WST not currently being met is the need for high reliability within the communications design of the systems.[102]

High reliability in WST is the assurance that connectivity and reliable transmissions are assured regardless of the operating environment.[103] High reliability will be required if WST is to have an application in home health and emergency situation usage. In addition, high reliability also has important security implications related to the safe transmission of personal medical data. For high reliability to be achieved, the sensors and sensor BANs will need to be able to transfer their information to a central data storage holder at any time without interference or loss of data.[104] Ideally, it should happen automatically to not burden the wearer with the need to download and transmit this data. However, not all current systems have automatic data transfers. If high reliability is not assured, the risk that data packets will not be transmitted in their entirety and only partial data packets will be received by the data analysis system is possible.[105] This risk could have serious consequences when the data is being analyzed for medication administration changes or other critical medical decision-making analysis. Incomplete data in this scenario could actually be more dangerous that no data at all.

Another major obstacle to high reliability communications is the challenge of maintaining signal connectivity amid obstructions and interference. When WST are being used within a structure, the walls and other obstructions impede the wireless signal transmission and connectivity decreases.[106] When WST has been used within buildings without an entire sensor system built into the structure, significant breaks in data transmissions and losses of data flow have created unnecessary emergency alerts.[107] It is not just solid walls that have been found to cause the interruption to the continuous flow of data. Some WST systems have been found to have dramatic interference of

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[102] Patel and Wang, "Applications, Challenges, and Prospective in Emerging Body Area Networking Technologies," 80–88.

[103] Ibid.

[104] Himayat, "M2M," 36–43.

[105] Ibid.

[106] Cao et al., "Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges," 2–3.

[107] Cao et al., "Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges," 2–3.

transmission as a result of “shadowing” created by the wearers’ body.[108] When the wearers’ body interrupts the direct line-of-sight, the absorption of the radio frequency energy, together with the movement of the wearers’ body, a significant and highly inconsistent communication pathway is created.

While the inability for the sensors to transmit their data due to interference is one concern, the ability for the sensors to be interoperable with each other and the systems with which they are attempting to communicate, is equally critical. Sensor nodes must be able to interoperate with each other, with existing networks, and in the home health and medical fields, with patient electronic medical record systems.[109] These demands will require the standardization of communication protocols, as well as data storage practices and formats. While the development of IEEE 802.15.1 (Bluetooth) and 802.15.4 (Zigbee) has allowed for standardization of communication protocols, no clear communication protocol is available for WST use.[110]

Wearable sensor technologies must be developed to be hierarchical in their data acquisition.[111] Currently, many of the system collect large quantities of data that are then analyzed for significant medical values. However, with the amount of data that current and future WST systems will produce, this system is prone to delays and missed data. For WST to function correctly, these systems must be able to measure large amounts of data continuously and then determine which microprocessors should process the data to determine which data requires immediate attention while ignoring non-useful data.[112]

This process of extracting critical data while ignoring the insignificant data is made more difficult by the need for multiple device transmission capabilities. This

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108 Patel and Wang, “Applications, Challenges, and Prospective in Emerging Body Area Networking Technologies,” 80–88.

109 Cao et al., “Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges,” 2–3.

110 James H. Aylor et al., “Body Area Sensor Networks: Challenges and Opportunities,” *Computer* 42, no. 1 (2009): 58–65.

111 Carmen C. Y. Poon, Yuan-Ting Zhang and Shu-Di Bao, “A Novel Biometrics Method to Secure Wireless Body Area Sensor Networks for Telemedicine and M-Health,” *IEEE Commun. Mag.* 44, no. 4 (2006): 73–81.

112 Poon, Zhang, and Bao, “A Novel Biometrics Method to Secure Wireless Body Area Sensor Networks for Telemedicine and M-Health,” 73–81.

feature will need to be able to handle the nearly simultaneous transmissions being received at the networks' base station from what could be a very large number of sensors and sensor systems. Support for these sensors will require upgrades to most network entry and re-entry protocols, as well as bandwidth request protocols.[113] Multiple connectivity options will aid in this problem to allow sensors to connect to devices and to each other. However, to connect on a scale needed for WST system communications, especially when many of the sensors will be constrained in range by power limitations, sensor arrangements that allow for reliable interworking between the many protocols will be necessary.[114]

Efficient communications and data processing will be essential for WST success; however, one final communications weakness must be addressed for WST to meet its high expectations. Priority access to communicate "emergencies" in a variety of cases must be ensured.[115] Current designs being used to communicate with WST do not allow for emergency or priority messages to take precedence over non-emergent transmissions. To achieve this level of communication, it may be necessary to rework bandwidth priorities and communication protocols within the systems.[116] An inability for priority or "emergency" data to be communicated to the correct agencies or individuals with absolute reliability would leave many users of WST lacking the emergency oversight WST has suggested it offers.

3. Sensor Limitations

Although each component of wearable sensor technology is important, the development and miniaturization of the sensors themselves is what has had the biggest impact on the realization of WST. Despite the successes and capabilities of modern sensors, weaknesses still present in their form and function. Some of the weaknesses observed in use are being obtrusive to the wearer, a lack of robustness, and an inability to

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113 Himayat, "M2M," 36–43.

114 Ibid.

115 Poon, Zhang, and Bao, "A Novel Biometrics Method to Secure Wireless Body Area Sensor Networks for Telemedicine And M-Health," 73–81.

116 Himayat, "M2M," 36–43.

yield reliable information regardless of environmental conditions, wearer position, or any other outside influence.[117] Sensors still have high power consumption and battery limitations negatively affect WST system's abilities to communicate and process data reliably.

Wearable sensors need to be biocompatible and unobtrusive. Although the different types of WST are made up of different components, the need for the materials to perform with the wearer is critical to the success of the technology. The sensors themselves will also need to remain small despite the increasing amounts of data retrieval that they are being asked to perform. Sensor size should remain unobstructed to the wearer's movements and daily activities, be ergonomic in their design and placement, and be easy to put on if they are going to be placed by the wearer.[118]

Another weakness with the sensors is the need for zero maintenance and fault recovery.[119] Ease of maintenance will be an essential component for WST use by wearers. If the wearer is required to perform regular maintenance on the sensors or other system components, wearer frustration with the lack of consistent reliable data will outweigh the benefits the technology was intended to have. The ability of the sensors to self-calibrate will be a critical issue when used in the home health monitoring environment.[120] It will be important to ensure that the data being recovered from the sensors maintain its accuracy over time.

Fault recovery and self-calibration will ensure enough reliability in the system to provide highly accurate data suitable for use when making medical diagnosis and guiding treatments. To help ensure it is achievable, the sensors and systems must be robust in their design. Many of the WST systems are designed to work in individuals' homes where the environment is controlled and stable. However, other systems are intended for use in the harsh environments of the battle field, fire grounds, and extreme sports worlds.

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[117] Ruzena Bajcsy et al., "Wearable Sensors for Reliable Fall Detection," in *27th Annual International Conference of the Engineering in Medicine and Biology Society* (Boston, 2005), 3551–3554.

[118] Ibid.

[119] S. Chetan, A. Ranganathan, and R. Campbell, "Towards Fault Tolerant Pervasive Computing," *IEEE Technol. Soc. Mag.* 24, no. 1 (2005): 38–44.

[120] Chetan, Ranganathan, and Campbell, "Towards Fault Tolerant Pervasive Computing," 38–44.

Regardless of the intended location of the systems use, the sensors and system must be tough enough to withstand the taxing environments they may face, such as physical, electrical and electro-magnetic threats, and should not be easily broken or compromised.[121] A current struggle with WST is that the monitoring of ambulatory wearers provides far more accuracy in collecting some biosignals than others.[122] It has been seen that some measurements are easily made useless by artifact caused by movements, such as shivering or tremors creating non-medically significant data, and rendering those data signals useless for diagnosis or treatment determinations. Artifact is any disturbance or alteration of medical data created by anything other than the physiologic system being assessed. An example would be a person shivering while having an EKG performed that would create waves on the EKG that are not truly related to the heart's activity, but instead reflect the electrical activity of the skin's movement. The need to reduce the amount of attenuation of motion artifact will be critical to the development of successful WST.[123] One of the most successful ways that this reduction has been accomplished has been through the integration of sensors into tight fitting garments. However, sensors within garments immediately put a limit on the number of sensors that can be integrated into the garment. In addition, garment sensor designs generally require a long design, development, and validation cycle that has resulted in delaying motion artifact reduction in WST.[124] This delay is currently seen most clearly in efforts to perform continuous monitoring of respiratory effort. Wearable respiratory sensors currently in use face a major hurdle due to their inability to eliminate background artifact caused by sensor motion and slippage. Sensors that are too lose become unable detect and report any accurate data, while those that are tightly secured around the body result in wearer discomfort and increased effort to breath.[125]

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[121] Korhonen, Parkka, and Gils, "Health Monitoring In the Home of the Future," 66–73.

[122] Ibid.

[123] Chetan, Ranganathan, and Campbell, "Towards Fault Tolerant Pervasive Computing," 38–44.

[124] Chetan, Ranganathan, and Campbell, "Towards Fault Tolerant Pervasive Computing," 38–44.

[125] Danilo DeRossi et al., "*A Comparative Evaluation of Different Techniques for Ambulatory Monitoring of Respiratory Rates* (Pisa: University of Pisa, 2008).

The monitoring of multiple vital signs from a remote location has proven challenging to achieve because the specialized sensors needed to perform those measurements were either unavailable or too expensive to be used.[126] As a result, almost all commercial wearable sensors in early attempts at health monitoring were limited to the measurement of only one physiological sign.[127] This limitation resulted in incomplete information and told the monitoring agency nothing about other relevant physiological conditions or environmental factors that might be affecting the wearer's health status. Current sensors have shown significant improvement in their ability to read multiple vital sign measurements. Those sensors being designed and tested for future WST appear to have no difficulty in multiband sensing and data acquisition.[128]

Reluctance on the part of some medical professionals to accept and assess the large data loads created by WST has been an issue that is yet to be resolved. As a result the full implementation of at home, mobile health monitoring has been delayed.[129] Multiple reasons may cause this delay; primary among them is the technological inability to retrieve the information, as well as the reluctance of physicians to work for "free." For WST in the healthcare field to be useful, it needs to be able to be accessed and analyzed by a medical professional.

WSTs produce a large amount of data for each wearer, which results in copious amounts of data coming into the physician's office from patients employing WST for home health monitoring. Since this data is private medical information, the doctor's offices have a requirement to have a system in place that can receive and store all the data, while protecting the privacy of each patient. Thus, a very large storage capacity and cyber-security systems are needed that are currently not in use by most physicians. In addition, physicians are reluctant to use WST because of the lack of clarity on how

[126] Lymberis and Dittmar, "Advanced Wearable Health Systems and Applications—Research and Development Efforts in the European Union," 29–33.

[127] Poon, Zhang, and Bao, "A Novel Biometrics Method to Secure Wireless Body Area Sensor Networks for Telemedicine And M-Health," 73–81.

[128] Ibid.

[129] Lymberis and Dittmar, "Advanced Wearable Health Systems and Applications—Research and Development Efforts in the European Union," 29–33.

billing and Medicare view WST as a medical procedure. The ability to bill patients or their insurance agencies for assessments done while the patients are at home and not in the physician's office have lead many physicians to fear that they will not be compensated for their time.

Significant challenges must be overcome before WST can be implemented on a large scale. Power consumption and battery capabilities appear to be the most significant technical issues for WST.[130] Although extensive research has been conducted, and many technological resources put into creating smaller batteries for WST systems, the desired size to power duration gap has not yet been achieved. A commercial lithium ion-polymer battery currently allows autonomy of up to seven hours of functioning. This 7-hour limitation does not meet the medical expectations of WST capabilities of around-the-clock monitoring and data collection.[131] As a result, energy recovery or power scavenging is currently being explored as a solution. By harnessing the energy created by the wearers' movements or heat, the life of the batteries supporting the system will be expanded. Research and design modifications continue since they currently are too inefficient to be useful.[132]

Researchers are testing the potential for flexible solar cells or textile coils, as well as improvements in battery technology in an effort to solve these power challenges.[133] Prototype flexible batteries, which are being designed specifically for WST usage, have shown the capability of increasing battery autonomous functioning time up to two additional hours.[134] Energy harvesting itself is a technological battle since different energy sources have widely varying energy availability. A solar panel, for example, exposed to uninterrupted outdoor sunlight creates up to 15 megawatts per square

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[130] Davide Curone et al., "Long-Distance Monitoring of Physiological and Environmental Parameters for Emergency Operators," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2009, 5159–5162.

[131] Ibid.

[132] Poon, Zhang, and Bao, "A Novel Biometrics Method to Secure Wireless Body Area Sensor Networks for Telemedicine and M-Health," 73–81.

[133] Ibid.

[134] Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

centimeter, but the same solar panel only makes 10 microwatts in response to indoor lighting for the same area.[135] Another potential solution to the power consumption rate and battery size concern is the use of super capacitors and carbon-nanotube-based energy stores that have demonstrated outstanding potential to increase battery capacity, but have not been developed to be commercially available.[136] The lack of reliable and consistent power has created ceilings on both computational and radio communications. As a result, "collaborative algorithms with energy aware communication" have had to be created.[137]

4. Wearer Limitations

Protective, and even stylish clothing, has been shown to create "feelings" of well-being. Clothing now has the capability to improve people's actual well-being when embedded with wearable sensor technologies. For designs of WST garments to be successful, they must embrace the hybrid mix of technologies that now exist, as well as meet the needs of potential wearers.

In the earliest phases of development, WST garments were somewhat crude prototypes. Their materials, stitching, and fit left the wearers uncomfortable and only able to tolerate the garment for short periods of time. As technology is being refined and prepared for commercial use, form and function will be critical to its success. If the garment is not aesthetically appealing to the wearer, or function in the manner intended, the wearer will not don the garment and any potential benefit is lost. "Form" is the aesthetic concerns, while "function" focuses on the genetic demands of the human body, the specific requirements of the wearer, and the functional objectives of the garment.[138]

For WST to be accepted, garment designers will need to investigate the daily lifestyle expectations of the wearers in terms of their behaviors, environments, and peers groups. Understanding the needs and lifestyles of the wearers will generate a better

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[135] Aylor et al., "Body Area Sensor Networks: Challenges and Opportunities," 58–65.

[136] Patel and Wang, "Applications, Challenges, and Prospective in Emerging Body Area Networking Technologies," 80–88.

[137] Cao et al., "Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges," 2–3.

[138] Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

understanding of and appreciation for the requirements the clothing will need to meet and the application of developing technologies. The resulting garments must have the correct functionality and usability for the specific users for which the garment is designed.

5. Fit and Range of Motion Issues

Since WST is still in development, no current fit or range of motion (ROM) concerns beyond those of the designers and system developers have been raised as they prepare to create smart garments for mass usage. An understanding of the needs of the wearer or end-user will have a significant impact on the design of the garments concerning their wearability, durability, weight, ease of motion, and garment care.[139] Designers creating WST for commercial sales can improve their designs by developing an understanding of the human physiological issues that will impact the designs of their garments. An understanding of the needs of the wearers' body is always factored into everyday clothing will be especially critical in the design of WST garments. The comfort of the garments they create will be impacted by the correct styling relating to sizing, cut and fit, as well as positional posture concerns and the ergonomics of the body's natural movements.[140] Ideally, a garment should improve and support the wearer's body without limiting its ability to move.

Products created to be attractive, comfortable, and technologically functional will benefit from the use of "'passive smart', 'active smart', 'very active smart' and 'intelligent' materials, which will add to the comfort and functionality of the garments."[141] "Passive smart" materials are those that "can sense the environmental stimuli" around them, while "active smart" materials "can sense and react to the condition of the stimuli."[142] "Very smart" materials can "sense, react and adapt to the

139 Upkar Varshney, "Pervasive Healthcare And Wireless Health Monitoring," *Mobile Networks And Applications* 12, no. 2–3 (2007): 113–127, doi:10.1007/s11036-007-0017-1.

140 Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

141 Jane McCann and David Bryson, *Smart Clothes and Wearable Technology* (Cambridge: Woodhead Publishing, 2009).

142 Ibid.

stimuli," while "intelligent" materials are those capable of "responding in a pre-programmed manner."[143]

Although this technology is new, it is already being used by outdoor outfitters like W. L. Gore. W. L. Gore uses the terminology "comfort mapping" to market the outer layer garments they manufacture.[144] "Comfort mapping" involves the application of breathability, abrasion resistance and thermal regulatory features in their garment designs through the fabrics they use in concert with the garments cut and stitching.[145] Gore's "comfort mapping technology" separates the wearer's body into separate zones that are rated to have different temperature ranges and limits. This "zonal" arrangement provides the foundation for the choices available of material combinations in their garments. A similar method is used by Patagonia in its BioMap fleece products. Patagonia advertises that its BioMap fleece "puts performance where your body needs it through strategic placement of variable-knit zones that address: warmth, dryness, cooling, mobility and fit."[146] Similar considerations of variable knits and materials will be needed to ensure the proper fit and performance of WST.

Clothing and textile designers tasked with WST garment creation will require an understanding of the components and needs of each garment system to provide for the collection and reading of the wearers vital signs from the surface of the wearers' body. They will be required to consider where the sensors should be placed on the garment and how tightly fitting the garment needs to be for the sensors to perform properly.[147] The relationship between common movement patterns and posture, as well as body surface curves and individual distortions, will have a major impact on how designs will need to vary to match the body to avoid potential problems imposed by the garment design. A garment that is "ignorant" of these issues may have negative effects on the wearers' range

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[143] Ibid.

[144] Gen'ichi Taguchi, *Introduction to Quality Engineering* (Tokyo: The Organization, 1986).

[145] McCann and Bryson, *Smart Clothes and Wearable Technology*.

[146] McCann and Bryson, *Smart Clothes and Wearable Technology*.

[147] Lymberis and Olsson, "Intelligent Biomedical Clothing for Personal Health and Disease Management: State of the Art and Future Vision," 379–386.

of movement, mobility, and ability to perform rapid repetitive movements.[148] Awareness of these issues by the designers should influence their garments' design and the selection of the smart textiles they use.

While most clothing items are sized as "small," "medium" and "large," for WST garments, such sizing methods will be insufficient for the different range of needs, uses, and end users. It may become necessary to create measurement charts that create more ideal fits for individual wearers. The development of engineered knitted materials and woven fabrics created by a medley of fabric and yarn properties will provide these garments with functionality that will be integral to their successful use. A key value to these knitted materials and fabrics is their ability to stretch. Stretch will be critical to the correct placement of sensors that must be securely placed in specific locations within a garment to match the anatomical locations from which the sensors must collect data.[149]

In creating a functional design that will successfully operate regardless of the uniqueness of each wearer's body, both the design and the shape will need to work together to merge into a clean and aesthetically pleasing style. For smart clothing to be successful, it must be able to form a symbiotic relationship between the styles of textile-based materials, and the design needs of the technological systems to support the functional objectives they have been designed to perform. Technological advances are often initially rejected by an intended market due in large part to the fear of new technology and poorly designed user interfaces. A key to making WST garments user-centered is to ensure the controls or displays, for those garments, are attractive and easy to read by a wide range of users.[150] Other considerations in the design of smart garments will be an understanding of the environment in which the garment is to be used? Was it designed for indoor use, outdoor use, or a combination of the two?

An appreciation of the impact of the environments in which the garments will be worn will be required. The wearers' activities may be performed while in an indoor

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[148] Ibid.

[149] McCann and Bryson, *Smart Clothes and Wearable Technology*.

[150] Lymberis and Olsson, "Intelligent Biomedical Clothing for Personal Health and Disease Management: State of the Art and Future Vision," 379–386.

environment, or while exposed to the outdoors in unpredictable conditions, which may include rough terrain. In addition, the wearer may be subject to extreme ranges of temperature and environmental conditions. The design of WST garments must be able to account for these operational extremes while still being able to provide accurate, reliable data. WST designers must also consider the garments' role regarding heat retention, combating wind-chill issues, and avoiding the holding of moisture against the wearer's skin.[151] A final consideration for fit is the need for the designers to be mindful of the parts of the body that are more vulnerable to injuries. Designing should provide either additional protection for these areas or easy access to them in the event of an injury.

This chapter has discussed the way in which the use of WST has been targeted for utilization in the medical and home health fields. It has also discussed projections of increased need for improved home health monitoring in the future. It presented the financial motivation behind the use of WST in this field, and how the change in American culture towards people being active participants in their own health care and well-being has opened new markets for WST. Four different WST prototypes were analyzed for their specific capabilities as well. In the second half of this chapter, the details of the strengths and weaknesses of WST were discussed.

In Chapter III, the important issue of the cultural similarities and differences within the primary WST market demographics are outlined to better understand the challenges that may come with WST adoption.

[151] Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

III. WEARABLE SENSOR TECHNOLOGY PROTOTYPES

While numerous WST systems in design for the home health care field are available, only a few systems are being designed with application in the fire service as an intended field of use. This chapter explores the research and analysis of four different WST prototypes that have different designs using a combination of smart textiles, microcontroller boards or other sensing capabilities.

A. ANALYSIS OF WST PROTOTYPES

WST is no longer a conceptual idea that is years in the future. Most Americans are aware of it, and hundreds each day are joining the growing number of citizens wearing it.[152] The most common forms of wearable technology are smart watches and fitness bands that have exploded onto the scene in the last few years. However, many of these wearable devices are, in reality, nothing more than digital pedometers that count the wearers' steps taken, or heart rate monitors that count the pulse. Although technology does communicate these readings via Bluetooth to the wearers' phone or laptop, it does not meet the standards of the WST being explored for use in the fire service.

What distinguishes the WST being designed for the fire service is not only its ubiquitous design, but also its ability to sense and react to the changing needs of the wearer, and the quality of the diagnostics it can provide.[153] It will also have the ability to transmit data over great distances; thus, improving service and timeliness of response to the wearers' physiological needs. The use of non-invasive sensors and smart textiles are particularly well suited for human use in that they offer painless measurements without the risk of infections or the need for advanced medical training to don the sensors

[152] Sungmee Park and Sundaresan Jayaraman, "Enhancing the Quality of Life through Wearable Technology," *IEEE Eng. Med. Biol. Mag.* 22, no. 3 (2003): 41–48, doi:10.1109/memb.2003.1213625.

[153] Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

properly.[154] However, the WST themselves do present a very highly complex system due to the inherent difficulty in measuring physiological signs from the body's exterior.[155]

The choice of which noninvasive device to use must be the one that meets the specific criteria needed while still being unobtrusive. Almost all past commercial wearable technology with applications in the health monitoring field have only been able to register a single physiological parameter.[156] It has resulted in transmitted information that was both incomplete and did not provide detail about other critical physiological and environmental considerations. For WST to be useful in the fire service, the garments and systems must be able to register multiple parameters simultaneously.[157]

WST garments have been produced that implement numerous different styles. The most common are the systems based on microcontroller boards, those based on the use of "smart textiles," and multi-sensor created mote-based BANs. However, as technology has improved, many of the prototype systems being tested today are hybrids of those systems. They include components of many systems banded together for heightened capabilities and communications. In the next few paragraphs, several products that have been or are being developed in WST are reviewed for their possible use within the fire service.

1. Georgia Tech Wearable Motherboard, aka "Smart Shirt"

The original project in the field of wearable technology was funded by the U.S. Department of the Navy in 1990. It was based on a proposal by Georgia Tech to create the world's first truly "smart textile."[158] The intent of the program was the development of a textile and garment that would allow for the detecting of possible garment/body

[154] Lymberis and Olsson, "Intelligent Biomedical Clothing for Personal Health and Disease Management: State of the Art and Future Vision," 379–386.

[155] Lymberis and Dittmar, "Advanced Wearable Health Systems and Applications—Research and Development Efforts in the European Union," 29–33.

[156] Shyamal et al., "A Review of Wearable Sensors and Systems with Application in Rehabilitation," 15–21.

[157] Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

[158] Curoni et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

penetration by projectiles, on the battlefield, and the subsequent monitoring of the wearers vital signs.[159] The research at Georgia Teach resulted in the development of the first wearable mother-board or “intelligent” material ever produced.[160] The GTWM, or the “smart shirt,” in its original design, used optical fibers to detect penetrating wounds with sensors and interconnections to monitor the body’s critical functions constantly under combat conditions.[161] Although the risk of penetration injury is much less in the fire service, the capability to monitor a firefighters’ vital signs during fire ground operations presented as a significant benefit available from the GTWM system. (See Figure 1.)

Figure 1. The Georgia Tech Wearable Motherboard

Source: “Georgia Tech Wearable Motherboard™: The Intelligent Garment for the 21st Century,” accessed April 12, 2015, http://www.gtwm.gatech.edu/.

The GTWM was the first garment that used “smart textiles.” However, as development continued and fine-tuning took place, it was realized that the use of “smart textiles” alone did not cover all the potential needs of the military or private users. In response, the GTWM design team developed the first hybrid system comprised of “smart

[159] Curoni et al., “Smart Garments for Emergency Operators: The ProeTEX Project,” 694–701.

[160] Jayaraman and Park, “Enhancing the Quality of Life through Wearable Technology,” 41–48.

[161] Chandramohan Gopalsamy et al., “The Wearable Motherboard?: The First Generation Of Adaptive And Responsive Textile Structures (ARTS) For Medical Applications,” *Virtual Reality* 4, no. 3 (1999): 152–168.

textiles," but which allowed for the addition of other sensors to the garment so as to meet the needs of the wearer.[162] The fire service can take advantage of this capability by adding sensors to detect and measure carbon-monoxide and carbon dioxide levels or monitor oxygen levels in a room. This data, paired with the firefighters' vital signs, could be communicated wirelessly to the IC where the data could be continuously observed providing appropriate information to the firefighters and their supervisors from which critical decisions, such as the need to evacuate the structure, may be made.

The design of the GTWM was a monumental advancement in the combining of textiles and computing. The Georgia Tech research and development in WST have brought about a shift of thought from solely of textiles to an understanding of "fabric is the computer."[163] The development of interconnected technology now allows for a flexible and wearable system that allows sensors to be connected that can monitor a variety of vital signs, including: heart rate, respiratory rate, EKG, pulse oximetry (saturation of peripheral oxygen or SpO2), and temperature, to name but a few.[164] The current GTWM allows these sensors to be plugged in anywhere on the shirt, although most specific sensors must be in specific locations for ideal data recovery, and are easily plugged into the GTWM garment. Once the desired sensors are in place, the flexible sensor bus (which is designed into the garment) directs the data from the sensors to a smart shirt controller that is also a component of the garment.[165] The controller then wirelessly communicates the information to a device, such as a PDA or personal computer, or over the Internet if it is using an appropriate communication protocol. This system allows the GTWM to fulfill the roles of being both an information system that permits computing and a system capable of monitoring and collecting the vital signs of the individual wearing it.

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[162] Gopalsamy et al., "The Wearable Motherboard?: The First Generation Of Adaptive And Responsive Textile Structures (ARTS) For Medical Applications," 152–168.

[163] Diana Marculescu et al., "Electronic Textiles: A Platform for Pervasive Computing," *Proceedings of the IEEE* 91, no. 12 (2003): 1993–1994, doi:10.1109/jproc.2003.819607.

[164] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

[165] Gopalsamy et al., "The Wearable Motherboard?: The First Generation Of Adaptive And Responsive Textile Structures (ARTS) For Medical Applications," 152–168.

Since the goal of the GTWM was to design a functional and wearable information collecting garment, user requirements for the system were established early in the process.[166] These requirements included factors, such as functionality, usability, wearability, durability, manufacturability, maintainability, affordability, and connectivity.[167] In its original design, the functionality of the GTWM included the ability to detect a penetration of the garment. However, for the fire service, the functionality is less demanding and requires only the expectation that vital signs will be accurately monitored and communicated, as well as that any added sensors will also function and communicate as needed. Requirements for the fire service include the ability to provide thermal protection, resist electromagnetic interference (EMI), offer hazard protection, and provides flame and heat mitigation.[168]

Wearability mandated that the GTWM not be burdensome in its weight, be breathable, comfortable to wear, and be quick to don and to take off. Additionally, it must provide easy access in the event the wearer needs medical treatment. It is critical that wearers not be hampered in any way from performing their jobs because of the presence of the GTWM garment. Studies have found that they have succeeded in that objective.[169] In an effort to improve wearability, the GTWM is made of a polypropylene fiber for comfort, spandex for ensuring a proper snug fit, and Nega-Stat™ for dissipating static.[170]

The durability of the GTWM is another critical component of its use. According to the Georgia Tech literature on their wearable motherboard garment, it "should have a life of 120 combat days and withstand repeated flexure and abrasion."[171] Due to the humidity to which the GTWM will be exposed from the environment in which it is used,

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[166] Sungmee Park and Sundaresan Jayaraman, "Smart Textiles: A Platform for Sensing and Personalized Mobile Information-Processing," *Journal of the Textile Institute* 94, no. 3–4 (2003): 87–98.

[167] Ibid.

[168] Marculescu et al., "Electronic Textiles," 1993–1994.

[169] Babak Firoozakhsh et al., "Wireless Communications of Vital Signs Using the Georgia Tech Wearable Motherboard," in *2000 IEEE International Conference on Multimedia and Expo*, 2000, 1253–1256.

[170] Marculescu et al., "Electronic Textiles," 1993–1994.

[171] Marculescu et al., "Electronic Textiles," 1993–1994.

as well as a result of the anticipated perspiration of the wearers, the systems and technology used within it were made to be corrosion resistant.[172]

The ability to manufacture the GTWM will be another consideration, as eventually, the designers of this garment estimate it will need to be manufactured in large quantities to meet widespread demands. Garments must be designed to be compatible with the standard clothing and equipment worn by the specific individual.[173] Durability is important, but no more so than the ability of the garment to withstand daily use and necessary cleaning. The ability to maintain the GTWM is a critical consideration for the hygiene and comfort of the wearer. It must to be able to withstand routine cleaning, be able to dry quickly and be easily repairable if it sustains minor damage.

Another requirement for WST is ease of connectability. This connectability has a dual meaning with the GTWM, as it covers both the ability of the wearer to connect any additional sensors, and the garment's ability to connect to its controller and wirelessly transmit data to desired locations.

The GTWM has been tested by the United States Navy and United States Army with very good results regarding its ability to collect and transmit the vital signs of its wears.[174] The EKG leads used in the GTWM are the same type of electrodes found in both the pre-hospital and clinical setting. Instead of being part of the GTWM garment, the electrodes are placed on the wearer's body and then worn under clothing as would be done when in normal use. After testing, the subject was then wired into an EKG at Crawford Long Hospital and another EKG was acquired in normal medical fashion. It was determined that the quality of the GTWM EKG and the hospital acquired EKG had almost no difference in their readability or accuracy.[175]

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[172] Ibid.

[173] Sundaresan Jayaraman, Kenneth Mackenzie, and Sungmee Park, "The Wearable Motherboard: A Framework for Personalized Mobile Information Processing (PMIP)," in *39th Annual Design Automation Conference* (New York: ACM, 2002), 170–174.

[174] Ibid.

[175] Firoozakhsh et al., "Wireless Communications of Vital Signs Using the Georgia Tech Wearable Motherboard," 1253–1256.

The final consideration for any wearable sensor is the affordability of the system. The anticipated cost to produce the GTWM "smart shirt" is in the $35 range.[176] This estimated cost does not include the need to have laptops or other devices that can receive the data communicated from the garment.

2. ProeTEX

Following the creation of the GTWM, the European Commission recognized this developing branch of research as having the potential to significantly impact in the information, communications and technology field.[177] The European Commission began funding studies researching the applications of wearable electronics in the medical field and in worker surveillance. One of these studies resulted in a European-integrated committee called ProeTEX, which was tasked with the creation of a "smart" garment that would incorporate sensors, communication, data processing, and power management devices that would be directly integrated into the textile structure of the garments.[178] The goal was to design this system specifically for emergency and disaster intervention responders, firefighters, and civil protection rescuers. ProeTEX was officially started in February 2006 and was made up of a collection of 23 partners from eight European countries.[179] Included in that consortium were 22 industrial companies, universities, and research centers throughout Europe.[180]

The ProeTEX committee realized in the early development of its product that structural firefighters have different needs when compared to other disaster responders, since they perform the majority of their work in smaller areas generally with specific boundaries. In addition, large numbers of firefighters generally do not need to be monitored concurrently. Often their interventions, such as forcible entry, establishing

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[176] Jayaraman et al., "The Wearable Motherboard: A Framework for Personalized Mobile Information," 170–174.

[177] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701

[178] Ibid.

[179] Annalisa Bonfiglio et al., *Managing Catastrophic Events by Wearable Mobile Systems* (Berlin: Springer, 2007).

[180] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

ventilation, and fire attack, can be tracked visually.[181] Nonetheless, the working environment for structural firefighters can be extremely dangerous due to the presence of fire, toxic gases, and explosions. It was determined that all these fire ground tasks and environmental dangers would need to be monitored by any system designed for use by the fire service, and should automatically generate alarms to the firefighters should extreme conditions be detected.

From discussions that the ProeTEX committee had with fire services throughout Europe, they were able to create a list of end-user specifications to help guide the development process.[182] According to the end-user requests, the desired monitoring parameters included the "heart rate, respiratory rate, body temperature, blood oxygen saturation levels, environmental temperatures, concentration of toxic gases, such as carbon monoxide and carbon dioxide, operators' activity, and the operator's absolute position and speed."[183] To meet the desires of the end users, ProeTEX designed its system to be made up of three sub-systems: an inner garment (IG), outer garment (OG) and a pair of boots.[184] (See Figure 2.) Each subsystem has at least one sensor linked to micro-processors that receive the data and send it to the system bus for transmission.

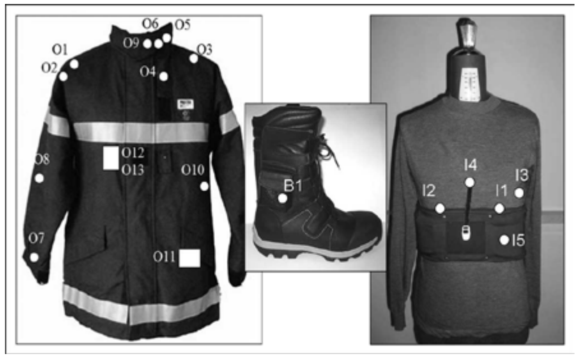
[181] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

[182] Laura Caldani et al., "Firefighters and Rescuers Monitoring through Wearable Sensors: The Proetex Project," in *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (Boston, 2010), 3594–3597.

[183] Bonfiglio et al., "*Managing Catastrophic Events," 95–10.*

[184] Caldani et al., "Firefighters And Rescuers Monitoring through Wearable Sensors: The Proetex Project," 3594–3597.

Figure 2. Overview of the Proe-TEX Prototype



(Left panel) OG—External temperature sensor (O1), heat flux sensor (O2), GPS antenna (O3), front visual alarm (O4), acoustic alarm (O5), collar and wrist accelerometers (O6 and O7), textile motion sensor (O8), CO sensor (O9), ZigBee module (O10), PEB (O11),Wi-Fi module (O12), and textile antenna (O13). (Central panel) Boot—CO2 sensor and ZigBee module housing (B1). (Right panel) IG—Textile electrodes for HR monitoring (I1), piezoelectric BR sensor (I2), BT sensor (I3), SPO2 sensor (I4), and VSB (I5)

Source: Davide Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," *IEEE Transactions on Information Technology in Biomedicine* 14, no. 3 (2010): 694–701.

The IG has a textile sensing component that is in direct contact with the wearers' skin. Composed of two knitted stainless steel electrodes, these sensors are located to ensure a good EKG signal is achieved from the garment.[185] In addition, the ProeTEX system has added a neoprene filler into the electrodes to improve the adherence needed to protect the skin/sensor connection even during strong physical activity.[186] These sensors not only provide the EKG signal, but also are the sensors that record and transmit the heart rate of the wearer.

To monitor the respiratory status of the wearer, a piezoelectric sensor is wrapped in a removable band that senses the stretch and recovery of the band to reflect the respiratory action of the wearer.[187] The band is adjustable to ensure the wearers are able to position the band in the correct location and that it is tight enough to stretch and recoil

[185] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

[186] Ibid.

[187] Caldani et al., "Firefighters and Rescuers Monitoring through Wearable Sensors: The Proetex Project."

accurately. A temperature sensor is also built into the garment, designed to contact the wearers under their left arms, which provides a continuous read of the wearers' skin temperature.[188]

The OG, like the IG, contains sensors, but unlike the IG that is primarily focused on monitoring of the wearers' physiological condition, the OG sensors monitor the environmental conditions in which the wearers are operating. The OG monitors such variables as the external temperature, the concentrations of carbon monoxide and carbon dioxide, as well as the location of the wearer within a building.[189] In addition, the wearers' posture, motion, and any falls can be observed through the addition of two accelerometers in the OG.[190] The firefighters' OG also contains one final sensor that measures the amount of heat radiating through the thermal barrier in the firefighters' bunker coat to determine the risk of injury to the firefighter from heat exposure.[191]

The core of the ProeTEX system is the professional electronic box (PEB) contained in the OG.[192] The PEB receives all the wireless communications that come from the subsystems to allow the real time transmission of data recorded by all the sensors contained in the wearer's garment, regardless of their location on the body in relation to the PEB. Information acquired by the PEB is simultaneously transmitted to the individual or system in charge of monitoring the wearers through the use of a "remote transmission system based on a Wi-Fi protocol."[193] Most civil protection and firefighting operational standards require a local coordinator of operations. This coordinator is often represented by an IC at a command post, which is ideally and most commonly located beyond the borders of the operational zone, but from a location at which all emergency responders can be overseen and directed. The command post is equipped with a software program operated on an interface with Google Earth®, which allows for multiple wearer

[188] Ibid., 3594–3597.

[189] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

[190] Ibid.

[191] Ibid.

[192] Ibid.

[193] Ibid.

data streams to be received. Locations of wearers can be depicted on a map of the operational area.[194]

The ProeTEX system is powered by a commercial lithium ion polymer battery that allows for up to seven hours of autonomous operations.[195] Also, a prototype flexible battery is specifically designed for the ProeTEX system, which will increase the usable time an additional two hours.[196] The OG is outfitted with an alarm system that will alert the wearer, as well as the supervising agent, in the event a dangerous situation is detected. These alarms may include warnings for the presence of high levels of carbon monoxide (CO) or carbon dioxide (CO2), which would require the immediate evacuation of the area. These alarms, like all other communications from the ProeTEX system, are transmitted using a "long-range transmission module."[197]

While many firefighters already carry and utilize commercial handheld toxic-gas monitors and activity sensors to detect prolonged periods of immobility, both these capabilities are already part of the ProeTEX firefighter suits. A CO2 sensor is built into the boot's upper section contained in a special pocket that leaves it capable of monitoring the air.[198] The CO2 sensor was located in the boot because CO2 is known to be heavier than air and will accumulate at lower levels first. The CO monitor was placed in the lapel of the jacket because it has a vapor density very similar to air and unlike CO2, it will not settle to the ground, but will maintain its ability to float.[199] To get ideal functionality of the toxic-gas sensors without exposing them to the hazards of the environment, the sensors are both placed on the outside of the OG. However, the sensitive electronics of the systems are safely located within the coat inside the thermal layer of the jacket to protect it from the heat and moisture common at fire grounds.

[194] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

[195] Caldani," Firefighters and Rescuers Monitoring," 3594–3597.

[196] Ibid.

[197] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

[198] Bonfiglio et al., "Smart Garments for Emergency/Disaster Operators," 3962–3965.

[199] Ibid.

As with all new products and technology, cost will be an important factor to potential users. ProeTEX, which is still in its trials phase, is unable to be exact on its costs, but has estimated that a ProeTEX system with all of its component parts will run between $5,000 and $5,500 USD.[200]

Unlike the GTWM, ProeTEX is much more than a garment worn under the usual clothing and equipment of the user. ProeTEX has developed an entirely new firefighter wearable system that includes multiple components that monitor the wearer, as well as the operational environment. According to Davide Curone, "It is now possible to have information infrastructures fully built into firefighting clothing that collect, process, and communicate data about the wearer and about the environment in which he or she is operating."[201]

3. VTAMN

The French company Medes, creator of the Vetement de Te'le' Assistance Medicale Nomade (VTAMN) project set a goal to "reach a higher level of electronic integration in clothing than had been previously achieved by the GTWM."[202] Its objective was to create a biocloth that would be comfortable and washable yet which incorporates connections, wires, and micro sensors directly into the garment. The aim of the VTAMN project was to be able to measure physical activity, as well as physiological parameters during the wearers' daily lives by creating a new design of sensor networks, as well as original distribution algorithms for sensor communication. The VTAMN system also was made to be able to request emergency services on its own through cell-phone links to assist in the rescue of the wearer in extremis. It is able to guide rescuers to the location of the wearer through the use of the global positioning system (GPS) sensor in the garment.[203]

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[200] Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

[201] Ibid.

[202] Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

[203] R. Baghai et al., "VTAMN—A Smart Clothe for Ambulatory Remote Monitoring of Physiological Parameters and Activity," in *26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (Boston, 2004), 3266–3269.

The VTAMN project, which began in January 2001, strove to incorporate biosensors and bioactuators into the textile it was creating through weaving them into the fabric.[204] The T-shirt component of the VTAMN garment uses dry EKG electrodes, a shock/fall sensor, a respiratory rate sensor, and two temperature sensors, as well as a GPS receiver. The ability to integrate and miniaturize microelectronics has allowed the development of micro sensors, such as the accelerometers and magnetometers that can be interwoven into the garment of the wearers to monitor their medical condition.[205] The VTAMN system is set to analyze the wearers' heart rate, respiratory rate, and activity level.

The VTAMN system is comprised of two main parts, the T-shirt and the belt. The T-shirt is comprised of the garment itself plus four EKG surface electrodes, a coil for respiratory status monitoring, two temperature sensors, and fall detection module, in addition to a wiring package, various interconnections, and the busses for the sensors.[206] The belt retains the "connection for the wiring, the main electronics board, the global system for mobile communications (GSM) and GPS modules, the batteries, and the EKG electronics."[207] The data and power supply electronics are arranged in a "bus-like configuration" known as a "Body-LAN."[208]

Different types of wires were explored during the design of the Body-LAN system in an effort to find which combination of wires would have the least power draw and create the least motion artifact. The final result was a blending of very fine stainless steel wires coated with silk.[209] In an effort to maintain comfort and functionality, the EKG electrode wires were placed in the T-shirt via weaving while all the other wires were embroidered into place. The EKG subsystem is an adaptation from the system used

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204 Axisa et al., "Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention," 325–336.

205 Baghai et al., "VTAMN—A Smart Clothe for Ambulatory Remote Monitoring of Physiological Parameters and Activity," 3266–3269.

206 Ibid.

207 Ibid.

208 Ibid.

209 Curone et al., "Smart Garments for Emergency Operators: The ProeTEX Project," 694–701.

in the 12 electrode Holtor monitor, which had long been the only technology available to monitor patients with suspected cardiac problems. For the VTAMN system, the Holtor monitor was simplified to record the cardiac rhythm using only four electrodes that are placed on the wearers' anterior deltoids and just above the anterior iliac crests. With these placement positions, the EKG sensors deliver an "acceptable" signal.[210]

Historically, "continuous monitoring of respiratory frequency is heavily plagued by motion artifacts."[211] Motion artifact is principally caused from sensor slippage while being worn, but if the sensors are tightly wrapped to the body to prevent slippage, they can become uncomfortable and even restrict breathing. The pneumograph subsystem in the VTAMN is an adaptation of a commercial pneumograph. Based on a two-coil design, this subsystem operates based on low amplitude impedance where changes in the chest volume result in differences in how the electricity flows through the chest cavity from one side of the coil to the opposite side of the coil.[212] These changes in chest cavity conductivity result in readings of actual ventilation rate. The pneumograph belt is positioned on the wearer around the upper abdomen to prevent it from blocking the EKG sensor locations while still allowing it to perform its function with high accuracy.[213]

The other sensors that comprise the VTAMN system are the temperature sensors and the fall sensor. (See Figure 3) For temperature readings, sensors are located in specific locations to ensure that the data being collected is accurate for its intended purposes. For temperature readings of the outside environment, a sensor is embedded on the outside of the shirt, while another sensor if placed within the shirt and given a special backing to isolate the measurements to ensure it only reads the middle layer and does not

[210] R. Baghai et al., "VTAMN—A New "Biocloth" for Ambulatory Telemonitoring," in *4th International IEEE EMBS Special Topic Conference on Information Technology Applications in Biomedicine* (Boston, 2003), 299–301.

[211] Rossi et al., *A Comparative Evaluation of Different Techniques for Ambulatory Monitoring of Respiratory Rate*.

[212] Baghai et al., "VTAMN—A Smart Clothe for Ambulatory Remote Monitoring of Physiological Parameters and Activity," 3266–3269.

[213] Ibid.

assess and radiation from the outside. The fall sensor is a “2 axis accelerometer with a microcontroller that is embedded on a flexible sensor board” and positioned within the belt.[214]

Figure 3. Fall Sensor Location on VTAMN

Source: “VTAMN PROJECT (RNTS 2000): “Medical Teleassistance Suit,” 2005, http://george.medes.fr/home_en/telemedicine/assistance_to_patients/vtamn.html.

In the development process, the VTAMN group made a conscientious effort to bring down the overall power demand of the system, originally done in an effort to reduce the size of the batteries required for the system, in hopes of being able to place the batteries in the T-shirt portion of the garment. However, as the batteries could not be reduced in size, and the power consumption could not be reduced further, a belt was added to the system to house the batteries.[215] Once the belt was added to the system, the main electronics board and the GPS/GSM modules were added to the belt as well.[216] The overall weight of the VTAMN system finished at 730g or just over 1.6 pounds with more

[214] Baghai et al., “VTAMN—A New “Biocloth” for Ambulatory Telemonitoring,” 299–301.

[214] Rossi et al., *A Comparative Evaluation of Different Techniques for Ambulatory Monitoring of Respiratory Rate*.

[215] Rossi et al., *A Comparative Evaluation of Different Techniques for Ambulatory Monitoring of Respiratory Rate*.

[216] Ibid.

than half of that weight coming directly from the rechargeable batteries, which have an operational life of over 18 hours.[217]

The projected costs of the VTAMN system are unknown as this technology is still in research and development.

4. MagIC

In 2005, an Italian research group created their first prototype of a wearable garment it called the MagIC (Maglietta Interattiva Computerizzata) system.[218] (See Figure 4) The system was originally designed to gather cardiorespiratory data in elderly patients who lived in confined environments, such as nursing homes, hospitals, etc. It has now progressed in its design and function to include usage by those healthy individuals who seek to have their health monitored as well.

Figure 4. MagIC System Garment

Paolo Castiglioni et al., "MagIC: A Textile System for Vital Signs Monitoring. Advancement in Design and Embedded Intelligence for Daily Life Applications," in *29th Annual International Conference of the IEEE Engineering in Medicine And Biology Society*, 2007, 3958–3961.

The primary component of the MagIC system is its Lycra and cotton vest that has been integrated with sensors, as well as a "portable electronic board" to store the data

[217] Baghai et al., "VTAMN—A New "Biocloth" for Ambulatory Telemonitoring," 299–301.

[218] Marco Di Rienzo et al., "Magic System," *IEEE Eng. Med. Biol. Mag.* 28, no. 6 (2009): 35–40, doi:10.1109/memb.2009.934627.

acquired by the sensors.[219] The crucial issue in the design and development of the MagIC garment was in the choice of the textile and its technological capabilities. The designers had to create a way for the sensors to provide good connectivity on the wearer's skin but not rely on adhesives to accomplish that connection.[220] It was critical that the connections between the sensors and skin were also maintained during physical activity. It was determined that the simplest ways to achieve this goal was to increase the compression of the garment on the wearer. This approach prevented sensor movement on the skin and resulted in decreasing motion or signal artifact.[221] The MagIC research group also concluded that the fabric and cut of the garment played a role in the amount of artifact created by permitting as much freedom of movement as possible without disturbing the sensors and their adherence. To balance the need for freedom of movement with the need for proper sensor adhesion, a large range of sizes of the MagIC system were produced.[222]

When the MagIC research and design group expanded the use of MagIC outside the clinical monitoring of the elderly, changes to many of their original paradigms needed to be addressed. Once healthy subjects were brought into the target populace, the rates of potential motion artifact from movement, exercise, and other activities increased substantially. In addition, it was realized that the garment itself would be placed under much more extreme and stressful conditions requiring a reassessment of the garments durability.

In the original design, sweating was not considered to be an issue; however, it also needed to be addressed with the expanded use of the MagIC system. In its own research, MagIC documented, "Only during heavy or prolonged physical activity or

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[219] Marco Di Rienzo et al., "MagIC System: A New Textile-based Wearable Device for Biological Signal Monitoring. Applicability in Daily Life and Clinical Setting," *2005 IEEE Engineering in Medicine and Biology 27th Annual Conference*, 2005, 7167–7169.

[220] Bruno Borodoni et al., "MagIC System," *IEEE Engineering in Medicine and Biology Magazine* 28, no. 6 (2009): 35–40.

[221] Paolo Castiglioni et al., "MagIC: A Textile System For Vital Signs Monitoring. Advancement In Design And Embedded Intelligence For Daily Life Applications," in *29th Annual International Conference of the IEEE Engineering in Medicine And Biology Society*, 2007, 3958–3961.

[222] Di Rienzo et al., "MagIC System: A New Textile-based Wearable," 7167–7169.

while exposed to warm environments, the wearing of the garment may induce abundant sweating that soaks the vest. In these exceptional cases, the wet vest may be unpleasant for the subject, although this fact does not interfere with signal quality."[223] MagIC has begun addressing the problem of sweating and comfort by testing new yarns and textiles to permit better evaporation in subjects exposed to environments like those frequently faced by firefighters.

The EKG read is made using two woven electrodes composed of conductive fibers. Despite the few number of electrodes used, the data recovered from this electrode design have shown the MagIC EKG signal "provided readable signals more than 99% of time when the patient was laying supine and 95% of the time when the patient was actively moving."[224] In all instances of readable signal recovery, the data allowed for the identification of all abnormal cardiac rhythm disturbances.

The respiratory sensing capabilities of the MagIC system come from the textile-based piezoresistive transducer that measures the respiratory rate through changes in the thoraxes volume.[225] The transducer is a "thin elastic cord made of textile yarn" able to conduct an electrical impulse, which is surrounded in an elastic core.[226] As a breath is taken, the movement of the chest results in a change in the volume of the thorax. This change in volume created by the respiration results in the cord stretching and a consequent alteration in its resistance indicates a breath has been taken.[227] Connections made by the conductive fibers, the respiratory data, as well as the EKG data, are fed to an electronic board that is securely positioned on the vest.[228]

The wearers' movements and activity level is the final measurable data acquired by the MagIC system. MagIC is able to detect movement and activity level through the

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[223] Ibid.

[224] Ibid.

[225] Marco Di Rienzo et al., "MagIC System," *IEEE Engineering in Medicine and Biology Magazine* 6, no. 28 (2009): 35–40.

[226] Di Rienzo et al., "MagIC System: A New Textile-based Wearable," 7167–7169.

[227] Di Rienzo et al., "MagIC System," 35–40.

[228] Ibid.

imbedded three axis accelerometer in the vest.[229] The electronic board then stores the signals from the accelerometer or a memory card and can then transmit that data via Bluetooth or Zigbee to a computer or personal digital assistant (PDA).[230] This data is currently only available for display on time plots, which makes the information difficult to assess and less useful in monitoring real-time activity.

As with all wearable technology, a critical component of the MagIC system is its power supply. The MagIC system uses a 3.6V rechargeable battery with an estimated life of over 60 hours.[231] This estimation is based on all data being stored in the electronic board and does not account for transmitting the data from the garment to an external device.

Although MagIC has been in development for over 10 years, because of the number of changes and prototypes that have been developed, the MagIC designers have not yet been able to estimate a cost for their product. A response to questions regarding the estimated costs for the MagIC system by its designers went unanswered when requested by this author.

B. SUMMARY

Many different styles and designs of wearable sensor systems have been made. The GTWM, ProeTex, VTAMN and MagIC systems are the four most developed systems that have marketed themselves as having been designed for use within the fire service. While each of these systems has its advantages, each also has its draw-backs and limitations. Based on this research, it is clear that power consumption concerns created by weight and size limitations are a hurdle that each system shares. Although some of these systems have advertised battery life spans that lasts a sufficient amount of time for firefighting operations, the primary reason for their prolonged battery life is the decreased number of sensing capabilities and communication capabilities. Those systems that have

[229] Di Rienzo et al.," MagIC System: A New Textile-based Wearable," 7167–7169.

[230] Ibid.

[231] Ibid.

the shorter battery lifespans have a corresponding larger number of sensing and communication capabilities.

Table 1 illustrates the point comparison between the four WST systems analyzed in this research. It demonstrates the capabilities and limitations of each system.

Table 1. Point Comparison between the FOUR WST Systems

Evaluation Criteria		Georgia Tech Wearable Motherboard	ProeTEX System	VTAMN System	MagIC System
Wearability:					
	Comfort	Yes	Yes	Yes	No
	Skin Irritation	No	No	No	Some
	Lightweight	Yes	Yes	No	Yes
	Breathable	Yes	Yes	Yes	Some
	Moisture Absorption	Yes	Yes	Yes	No
	Easy to Don & Doff	Yes	Yes	Yes	Yes
	Easy Access to Body	Yes	Yes	Yes	Yes
	ROM Limitations	No	No	No	No
Durability:					
	Flexural Endurance	Yes	Yes	Yes	Yes
	Tear Resistance	No	Yes	No	No
	Abrasion Resistance	No	Yes	Yes	Yes
	Heat Resistance	Yes	Yes	No	No
	Moisture	Yes	Yes	Yes	No

Evaluation Criteria		Georgia Tech Wearable Motherboard	ProeTEX System	VTAMN System	MagIC System
Wearability:					
	Resistance				
Maintainability:					
	Launderable	Yes	Yes	Yes	Yes
	Software Upgrades	Yes	Yes	Yes	unk.
	Rechargeable Battery	Yes - unk	Yes 9 hrs	Yes 18 hrs	Yes 60 hrs
Functionality:					
	Monitor Vital Signs	Yes-full	Yes-full	Yes-full	partial
	EKG Capability	4-lead	2-lead	4-lead	2-lead
	Communicate with External Device	Yes	Yes	Yes	No
Additional Sensing Capabilities:					
	CO/CO2 Monitoring	Optional	Yes	No	No
	Activity Monitoring	No	Yes	Yes	Yes
	True RR Reading	No	Yes	Yes	Yes
	Fall Detection	Optional	Yes	Yes	Yes
	GPS	No	Yes	Yes	Yes

The next chapter discusses the specific uses of WST within the fire service including scenarios.

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IV. WEARABLE SENSOR TECHNOLOGY IN THE FIRE SERVICE

WST has the capability to decrease LODDs from cardiac events because of its ability to monitor and communicate the physiological functioning of firefighters continuously while they are in the performance of their jobs. It has been well documented that firefighters are exposed to numerous cardiac risk factors while on duty in addition to the known risk factors of modern Americans.[232] WSTs offer a technology that can ensure that any cardiac abnormalities or unacceptable limits of physiologic function will be immediately detected and that both the firefighter and the IC are alerted to initiate medical care. Some WSTs also have the added capabilities of being able to monitor the environmental conditions and track the location and movement of the wearer.[233] Environmental monitoring of the area in which firefighters are working assists in protecting them from unique detrimental environmental conditions that could increase the risk of sudden cardiac death (SCD). Location tracking can be used to protect the firefighter from areas of known danger and make rescue more rapid in the event of a collapse or becoming trapped.

The first section of this chapter focuses on the key uses of wearable sensor technology including physiological monitoring, hazardous environmental monitoring, and firefighter location tracking. The second section explores the challenges and concerns of the stakeholders for WST, including privacy, security, legal considerations, health information privacy, and finally union concerns and considerations. Next, the costs of WST are described that include the estimated financial costs associated with WST systems, but attempts to factor in the direct and indirect costs of a firefighter's LODD. Training considerations are also explored. This chapter concludes with a set of scenarios that demonstrates how WST in the fire service can be of value and positively change the unacceptable LODD rates in the fire service.

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[232] Linda Rosenstock and Jorn Olsen, "Firefighting and Death From Cardiovascular Causes," *New England Journal Of Medicine* 356, no. 12 (2007): 1261–1263, doi:10.1056/nejme078008.

[233] De Rossi et al., "*A Comparative Evaluation of Different Techniques for Ambulatory Monitoring of Respiratory Rate*.

A. KEY USE AREAS OF WEARABLE SENSOR TECHNOLOGY

The need for physiological monitoring of firefighters has been made clear by the consistent LODD toll suffered by the collective U.S. fire service. Annually, the U.S. fire service has over 100 firefighter LODDs, and the leading cause of death is from CHD.[234] While firefighters must be aware of their susceptibility to the same cardiac risk factors that most Americans face, such as hypertension, poor diets, a sedentary lifestyle, and stress, they have additional risk factors that put them at an even higher risk of CHD and sudden cardiac events.

Despite the numerous programs and projects that have aimed to decrease the number of LODDs, no significant changes have been seen in firefighter behavior or the number of firefighters dying while on duty.[235] Additionally, a clear connection has been established between the work firefighters do and the increased risk of cardiac events, such as heart attacks, strokes, and cardiac death.[236] The combined effects of the repetitive "sympathetic nervous system activation, intensive physical work, heat stress, dehydration, and environmental conditions leads to a significant cardiovascular strain."[237] As firefighters face these conditions on a routine basis doing their jobs, it is likely that these multiple stressors function to precipitate cardiac events in firefighters.

The physiological tests and parameters of firefighters that should be monitored are the EKG, heart rate (HR), body temperature, blood oxygen saturation (Sp02 or Sa02), respiratory rate (RR), movement, and body position of the wearer.

The EKG potentially provides the most important data on cardiac status that can be acquired outside of a medical facility to recognize the development of cardiac

[234] Kales et al., "Emergency Duties and Deaths from Heart Disease among Firefighters in the United States," 1207–1215.

[235] Kumar Kunadharaju, Todd D. Smith, and David M. DeJoy, "Line-of-Duty Deaths among U.S. Firefighters: An Analysis of Fatality Investigations," *Sciencedirect* 43, no. 3 (May 2011): 1171–1180, http://www.sciencedirect.com/science/article/pii/S0001457510004070.

[236] Kales et al., "Emergency Duties and Deaths from Heart Disease among Firefighters in the United States," 1207–1215.

[237] W. Jon Williams et al., "Physiological Responses to Wearing a Prototype Firefighter Ensemble Compared with a Standard Ensemble," *Journal of Occupational and Environmental Hygiene* 8, no. 1 (2011): 49–57, doi:10.1080/15459624.2011.538358.

distress.[238] "Any irregularity in the heart rhythm or damage to the cardiac muscle" causes an alteration in the normal electrical flow pattern within the heart, which will present on the EKG as abnormalities in the electrical pattern and indicate the presence of cardiac distress or myocardial death.[239]

While EKGs can often reflect the true HR of the wearer, as described in the previous paragraph, the HR and the EKG will differ at times. To ensure an accurate HR count is maintained, the need to monitor the HR in a way separate from the EKG must be employed. The monitoring of the firefighters' HR is not simply to see if it is present or absent, but to gauge its rate, rhythm and regularity, and grasp that the HR is one in a set of vital signs that need to be compared in relation to one another to come to an understanding of the physiological functioning of the wearer.

During actual firefighting operations, HRs of firefighters can be between 150–190 beats per minute.[240] In many cases, these rates exceed the "age predicted" and the measured maximal heart rates based on baseline tests of the firefighters.[241] Not only does the speed at which the heart is beating need to be considered, but the fact that while firefighting, many changes take place in the circulatory system as a whole that can alter the speed with which the heart beats, as well as the overall functioning of the body. In the early phases of firefighting, a significant percentage of the firefighters' cardiac function is rerouted to the "cutaneous circulation and working muscles."[242] As a result of these changes in the heart's functionality, its demand for oxygen increases, as well as the

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[238] Andrew Han Brainard et al., "The Prehospital 12-Lead Electrocardiogram's Effect on Time to Initiation of Reperfusion Therapy: A Systematic Review and Meta-Analysis of Existing Literature," *The American Journal of Emergency Medicine* 23, no. 3 (2005): 351–356, doi:10.1016/j.ajem.2005.02.004.

[239] Ibid.

[240] Williams et al., "Physiological Responses to Wearing a Prototype Firefighter Ensemble Compared with a Standard Ensemble," 49–57.

[241] Loren G. Myhre et al., *Relationship between Selected Measures of Physical Fitness and Performance of a Simulated Fire Fighting Emergency Task* (Ft. Belvoir, VA: Defense Technical Information Center, 1997).

[242] Larry Kenney, Narihiko Kondo, and Nigel Taylor, *Faculty of the Physiology of Acute Heat Exposure, with Implications for Human Performance in the Heat Health and Behavioral Sciences* (Wollongong, New South Wales, Australia: University of Wollongong, 2008), 341–358.

amount of stress placed on the heart.[243] The movement of blood to the cutaneous level is done primarily as a means to improve thermoregulatory control by allowing the blood to cool, as it is nearer the surface of the body where evaporative cooling can occur.[244] However, in the case of firefighters, this attempt by the body to control its thermoregulation is often defeated by the microenvironment created by the clothes the firefighters wear. For this reason, the need to monitor the body temperature of firefighters is important in decreasing firefighter LODDs.[245]

The highly encapsulating and insulating properties of the firefighters' protective ensemble, better known as "bunker gear," prevents evaporation, and thus, the natural cooling capacity of the body, which becomes especially true when the atmosphere around the firefighters exceed 698 degrees Fahrenheit.[246] At this temperature, the thermal stress experienced by firefighters comes primarily from the microenvironment that exists in the void space between the wearers' body and the bunker gear and the inability of the accumulated head to be evaporated or otherwise removed.[247] The result is that sufficient quantities of "metabolic heat and humidity" are held within the firefighters' bunker gear to cause significant thermal stress to the wearer.[248]

The heat and humidity to which the firefighters are now exposed will increase their core body temperature and place them at greater risk for injury or death. Much of this increased risk stems from the fact that an increase in the firefighters' "core body temperature" can result in "increased stress on the cardiovascular system through the redistribution of blood to the cutaneous circulation," and to a contraction of plasma

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[243] Williams et al., "Physiological Responses to Wearing a Prototype Firefighter Ensemble Compared with a Standard Ensemble," 49–57.

[244] Ibid.

[245] Ibid.

[246] J. Randall Lawson, *Fire Fighter's Protective Clothing and Thermal Environments of Structural Fire Fighting* (Gaithersburg, MD: U.S. Dept. of Commerce, Technology Administration, National Institute of Standards and Technology, 1996).

[247] Ibid.

[248] Ibid.

volume as a result of sweating.[249] An increase in the HR and hearts demand for oxygen will also occur as a result of the decrease in plasma volume, which, when combined with pre-existing CHD could precipitate a cardiovascular event.[250] It is because of these effects that much of the cardiovascular morbidity and mortality among firefighters "can be attributed to high incident radiant heat and metabolic heat stress resulting from physical exertion."[251]

Although the ability to track a firefighters' movements and body position is not a measurement of physiological value, the ability to monitor the wearers' movements and body position will be important in the use of WST in the fire service. On fire scenes, the WST wearers will rarely be inactive. Therefore, firefighters who become inactive while performing their job need to have their other monitored data assessed to ensure that their inactivity is not a result of a medical reason for. The ability to determine body position and movement will be helpful in justifying increases or decreases in HR and RR, based on the work being done or the conclusion of an assignment resulting in a few minutes of inactivity.

B. PHYSIOLOGICAL MONITORING SCENARIO

Engine 5 of the Central City Fire Department is on scene at a large commercial warehouse where fires are burning uncontrolled on the first and second floors. Upon receiving his unit's assignment from the IC to take his crew and enter the first floor for firefighting operations, Capt. Tanner and each member of his crew grab the tools they will need, don their air packs, and turn on their WST garment. The IC confirms to Capt. Tanner that he is receiving all four members of Engine 5's crew signals and clears them to make entry. After eight minutes working within the structure, Capt. Tanner begins to feel light-headed with chest tightness that he dismisses because he believes it might be the straps across his chest from his air pack. At the same time, the IC receives both an

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[249] José González-Alonso, Craig G. Crandall and John M. Johnson, "The Cardiovascular Challenge of Exercising in the Heat," *The Journal of Physiology* 586, no. 1 (2008): 45–53, doi:10.1113/jphysiol.2007. 142158.

[250] Williams et al., "Physiological Responses to Wearing a Prototype Firefighter Ensemble," 49–57.

[251] Tom LaTourrette et al., *Protecting Emergency Responders, Vol. 2: Community Views of Safety and Health Risks and Personal Protection Needs* (Santa Monica, CA: RAND Corporation, 2003): 39–47.

audible and visual alarm at the command post notifying him that Capt. Tanner's heart rate has increased beyond his acceptable threshold and that he has begun to display multiple cardiac rhythm changes.

The IC calls for the withdrawal of Engine 5 for medical evaluation and has the on-scene paramedic unit, Medic 2, respond to the entrance from which Engine 5 will be exiting. Upon exiting the building, Capt. Tanner is assigned to a medical evaluation. The paramedics on Medic 2 perform a complete cardiac exam, including a 12-lead EKG where it is found that Capt. Tanner is experiencing a heart attack. Capt. Tanner is then given his first dose of fibrinolytic medications and is transported to the nearest emergency department. As a result of the rapid recognition of the WST system, and the work done by the paramedics and emergency room staff, Capt. Tanner only has a two-day stay in the hospital before he is released with no significant cardiac damage.

Most fire deaths are not caused by burns, but rather by the inhalation of smoke created during the fire.[252] In almost all cases, the smoke incapacitates the victim so quickly that making an escape to a nearby exit is impossible. The synthetic materials that make up so much of a modern home and its furnishings produce dangerous substances when exposed to the high heat present during a fire.[253] This toxic environment develops as a fire starts and grows within a building consuming all the available oxygen, which results in a slow burning fire known as a "smoldering fire." During this smoldering phase, incomplete combustion occurs and the majority of the toxic gases are created.[254] Smoke is made up of many ingredients, mainly unburned particles, partially burned particles, and completely burned substances that can be so small that they can be pulled into the respiratory system of anyone not wearing the correct respiratory protection.[255] Of

[252] Kunadharaju, Smith, and DeJoy, "Line-of-Duty Deaths among U.S. Firefighters: An Analysis of Fatality Investigations."

[253] Robert F. Dyer, "Polyvinyl Chloride Toxicity in Fires," *JAMA* 235, no. 4 (1976): 393, doi:10.1001/jama.1976.03260300019022.

[254] Dyer, "Polyvinyl Chloride Toxicity in Fires," 393.

[255] Deric C. Weiss and Jeff T. Miller, *A Study on Chemicals found in the Overhaul Phase of Structure Fires using Advanced Portable Air Monitoring available for Chemical Speciation* (Salem, OR: State of Oregon Fire Service Policy Council, 2011).

greatest concern for environmental monitoring is the presence of the toxic gases that are a major component of smoke, but can remain present even after the smoke is gone.

The most common toxic gas found at fire scenes is CO.[256] CO can be deadly even in small quantities, as it replaces oxygen in the bloodstream, which occurs due to hemoglobin's stronger chemical attraction to CO than to oxygen (O2). Traditionally in the fire service, a CO reading of below 35ppm has been the point at which firefighters have been permitted to remove all respiratory protection.[257] However, CO has been proven to be a poor predictor of other chemicals presence at fire scenes.[258] Therefore, the removal of respiratory protection based on the reading of a single gas leaves firefighters susceptible to exposure to other common toxic gases present at fire scenes.

During testing by the Office of the State Fire Marshal of Oregon, it was found that at fires in which testing samples were assessed, the levels of nitrogen dioxide (NO2), acrolein, CO, arsenic, and mercury, all exceeded levels the National Institute for Occupational Safety and Health (NIOSH) has established as producing immediately danger to life and health (IDLH).[259] Chemicals found to be present at levels that were at NIOSH recommended exposure level—short term (REL-ST) were hydrogen chloride (HCl), benzene, formaldehyde, glutaraldehyde, hydrogen cyanide (HCN), and ozone (O3).[260]

While some chemicals present at fire scenes do seem to predict the potential presence of other chemicals, no one individual agent has been found dependable enough to forecast the presence of all the hazardous agents present at a fire scene. As a result, WST should provide for active monitoring for the most common and most dangerous toxic gases to which firefighters will be exposed.

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[256] James B. Terrill, Ruth R. Montgomery and Charles F. Reinhardt, "Toxic Gases from Fires," *Science* 200, no. 4348 (1978): 1343–1347, doi:10.1126/science.208143.

[257] LaTourrette et al., *Protecting Emergency Responders, Vol. 2: Community Views of Safety and Health Risks and Personal Protection Needs*, 39–47.

[258] Ibid.

[259] Weiss and Miller, *A Study on Chemicals found in the Overhaul Phase of Structure Fires using Advanced Portable Air Monitoring available for Chemical Speciation*.

[260] Weiss and Miller, *A Study on Chemicals found in the Overhaul Phase of Structure Fires using Advanced Portable Air Monitoring available for Chemical Speciation*.

Two methods to monitor the environmental conditions within hazardous environments are *point source* monitoring, and *ambient* monitoring.[261] In point source monitoring, a vacuum acquired sample is taken at the source of the contaminant or material. This handheld monitoring device is used to determine the presence of hazardous materials and hazardous environments. Ambient monitoring is performed by samples being taken in the immediate vicinity of the worker to test the environment in what is commonly called the "breathing region." This monitoring is often part of the worker's protective clothing and gives a more representative reading of the total atmosphere. Ambient monitoring is gas dependent because of the different vapor densities of the gases being looked for when monitoring the environment.[262] With some gases sinking while others rise, ambient monitoring may not be as effective as point source monitoring for overall scene safety; however, it is ideal for individual responder safety.

C. HAZARDOUS ENVIRONMENTAL MONITORING SCENARIO

The fire at a three-story apartment building is now out and the job of digging through the debris and extinguishing any remaining small fires now begins for Engine 5. It has traditionally been the time when firefighters have stopped using their breathing apparatus since smoke is not visible and the air appears to be clear. With a WST system, like ProeTEX, which has the capability to determine the presence of toxic gases, Engine 5 will know that at this time, even though the air appears clear, actually, lethal levels of CO, CO2, and hydrogen cyanide are coming off the rubbish piles through which they are going to be sifting. As a result of that data provided to them by the sensors in their WST system, they leave their breathing apparatus on and complete their job without exposing themselves to the toxic chemicals that could have deadly consequences.

1. Location Tracking

The ability for firefighters to move rapidly and safely inside a building during operations is critical for rescue, firefighting, and firefighter safety reasons. If firefighters

[261] Bernard Fleet and Hari Gunasingham, "Electrochemical Sensors For Monitoring Environmental Pollutants," *Talanta* 39, no. 11 (1992): 1449–1457.

[262] Ibid.

are performing a search and rescue mission, the ability to move rapidly throughout the building and ensure that every room is searched could be the difference between locating a missing person and a casualty. In firefighting operations, being able to move quickly to the room of origin and extinguish the blaze rapidly decreases the chances of building collapse, stops fire damage, and removes the immediate threat to those who might still be in the building.

In regards to firefighter safety, the ability to know where to go to locate a trapped or injured firefighter and the fastest route to get there could be the difference between life and death. Although technology like thermal imaging does provide improved visibility to firefighters in smoke filled environments, it does not provide firefighters with location tracking or overall scene coordination to move in the most efficient direction for the building in which they are operating. Although no current location tracking technology is on the market for structural firefighters today, promising research is being done that could make this technology available within the next decade.[263]

Navigation in a building during a fire is difficult regardless of the size of the structure. Due to the dense smoke created during a fire, visibility in a fire is generally only a few inches in any direction. Combine visibility constraints with the issues of an unknown structure layout, intense heat, and the threat of dangers, such as building collapse or holes in the floor, and the threats to firefighters in these environments become clear. The ability for firefighters and firefighting crews to be tracked will make their movements under these conditions safer and more efficient. Through a combination of command post (CP) guidance and heads-up display (HUD), firefighters in the future will have the ability to see their location overlaid on the floor plan of the building in which they are operating.[264] This overlay will allow the firefighters and firefighting crews to make knowledge-based decisions on direction of travel, escape paths, and search and rescue patterns.

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[263] Baghai et al., "VTAMN—A Smart Clothe for Ambulatory Remote Monitoring of Physiological Parameters and Activity," 3266–3269.

[264] David L. Tate, Linba Sibert and Tony King, "Virtual Environments for Shipboard Firefighting Training," *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality*, 1997, doi:10.1109/vrais.1997.583045.

The current technology available for personal location tracking of GPS is not a viable option for structural firefighters due to the weak signal of GPS transmitters being insufficient to penetrate walls. A new technology in design for firefighter location tracking utilizes (UWB radio signals that can penetrate structures and allow signals to be picked up by the indoor positioning system (IPS) receiver.[265] UWB radio is designed to be used for short-range and high data-rate links, which makes it ideal for WST usage. These UWB signals are transmitted over a very wide range of frequencies and are able to be picked-up by the IPS device, which can plot the signals location to within three feet of its actual location.[266]

This technology, although still in development, will need to be tested to ensure that it is able to detect and accurately track firefighters within the harsh conditions in which they work. This new technology will also need to be able to determine the body positions of the firefighters and determine their location despite the unique body positions firefighters generally move in, such as crawling. The use of accelerometers and gyroscopes may solve some of these issues because of their ability to communicate the actual position of the firefighter within the building. In the event of a floor collapse where the firefighters' position would be a mystery with modern technology, WST like ProeTEX, would be able to communicate not only the firefighters' current location within the building, but also their anatomical position and any movement from the firefighters. Testing in real-world situations will be the best means to ensure this technology is truly able to add the benefits expected of it.

2. Location Tracking Scenario

A fire in a four-story apartment complex has resulted in Engine 5 being assigned to perform firefighting operations on the third floor. At the command post, the IC is alerted that Capt. Tanner of Engine 5 is having EKG changes, as well as respiratory and heart rate changes that have caused his WST garment to notify the IC. Despite his

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[265] Administrator, "Revolutionary GPS Could Save Firefighters Lives," Getreading, 2008, http://www.getreading.co.uk/news/local-news/revolutionary-gps-could-save-firefighters-4255616.

[266] Ibid.

attempts to contact Engine 5 and Capt. Tanner over the radio, he has no success in reaching them. Due to the seriousness of this event, a MAYDAY operation is started with a rapid intervention crew (RIC) being activated to perform a search and rescue for Capt. Tanner and the rest of Engine 5. In the past, the RIC crew would be told of the original assignment location of Engine 5 and from that knowledge alone would have to perform a search without the ability in most cases to see clearly due to thick smoke. However, thanks to the GPS component of Capt. Tanner's WST, the IC is able to know the location of Capt. Tanner in the building along with each of the other members of Engine 5. The RIC crew is steered directly to Capt. Tanner's location where he is evacuated from the structure and turned over to the medical crew who were awaiting his exit.

D. STAKE HOLDER CHALLENGES AND CONCERNS

While the potential benefits of WST in the fire service are numerous, and the technological developments needed for WST to provide the needed services are still being achieved, fire departments and the collective fire service must consider residual considerations prior to implementing WST that discussed in the next section, which explores the privacy, security and legal considerations of WST. As part of the legal discussion, this research addresses how WST can be used in consideration of the HIPAA laws, and what labor union concerns exist regarding the use of this technology by their members.

1. Privacy, Security, and Legal Considerations

With the use of WST, human lives are directly involved. Failure to protect the personal privacy of a WST wearer could negatively influence the life of that person. Many of the sensor network applications in WST rely on technology that can create security weaknesses like the unauthorized "eavesdropping" and "denial of service attacks" (DOS).[267] Creating a complete list of potential methods of attack is by the nature of technology impossible. As soon as new technology is created to protect data, new

[267] Moshaddique Al Ameen, Jingwei Liu, and Kyungsup Kwak, "Security and Privacy Issues in Wireless Sensor Networks for Healthcare Applications," *J Med Syst* 36, no. 1 (2010): 93–101, doi:10.1007/s10916-010-9449-4.

attack methods are also created to try to break down firewalls and defeat protection technology. In addition, many types of attacks cannot be imagined by the designers until a technology system has been implemented and deployed. Therefore, protections will likely be a “band aid” post-production fixes. However, the most concerning types of attack that could be leveled against WST networks are “eavesdropping on medical data, modification of medical data, forging of alarms on medical data, DOS, and location tracking of the system users.”[268]

The threat of eavesdropping occurs as the user’s medical information is acquired, communicated, and then achieved on the system.[269] Those people trying to get access to this information illegally might try to break into the system electronically. This access can be done by snooping on radio communications that take place between the sensor motes and the recording data with which they are communicating. A second concern is when attackers are able to alter medical data during its collection, transmission, or storage.[270] This kind of attack could result in false system reactions, or failures of the system to react when it should. Modifying data can also be used to trigger alarms by creating a fictitious message that does not alter the actual data but causes the real data to be missed or ignored that will result in the same type false alarms or alarm failures. This intrusion can be accomplished by creating fake messages instead of modifying regular ones, such as when medical data is modified.[271]

DOS attacks are manifested by a “jamming” or “overloading of the system,” which results in the system being rendered unusable.[272] System overloading during the attacks results in legitimate data coming from the sensor motes being unprocessed and abnormal conditions or emergencies being unrecognized.

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[268] Frank Kargl et al., “Security, Privacy and Legal Issues in pervasive ehealth Monitoring Systems,” in *Mobile Business, 2008. ICMB’08. 7th International Conference on*, IEEE, 2008, 296–304.

[269] Ibid.

[270] Marc Langheinrich, “Privacy by Design—Principles of Privacy-aware Ubiquitous Systems,” in *Ubicomp 2001: Ubiquitous Computing* (Berlin Heidelberg: Springer 2001), 273–291.

[271] Kargl et al., “Security, Privacy and Legal Issues in pervasive ehealth Monitoring Systems,” 296–304.

[272] Ibid.

Despite attempts to make the information transmitted by WST garments secure, all WST, like all cell phones, leave behind them an invisible wake of electronic markers. Even with systems that have been designed to operate with "localization of persons," these electronic markers could still be gathered, grouped, and assessed to develop a very accurate location of the wearer's location.[273] A further threat present in the use of eHealth systems like WST, therefore, is the ability of persons or companies to track the activity of the wearers.[274] In this kind of tracking, recorded data from the wearer can be analyzed to measure the amount of activity a person is getting by observing heart rate patterns and oxygen saturation readings. This kind of data would be very desirable by insurance companies who may be tempted to misuse the data resulting in an alteration or decrease in benefits for those people they deem to have an unhealthy lifestyle.[275]

In an attempt to decrease the exposure to attacks on personal information of WST wearers, a security-minded approach to their use must be implemented that can be accomplished through implementing safeguard measures in three levels: administrative, physical, and technical.[276]

At the administrative level, "security measures should be applied to check for security breaches by staff or those people responsible for operating the system."[277] Creating a "well defined hierarchy" of the users, coupled with stout identification confirmation protocols, may aid in preventing violations within security systems on the administrative side of the operation.[278] In addition, a security measure at this level should include access mechanism that only allows authorized individuals to access the data.

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[273] Oliver Berthold and Hannes Federrath, "Identitaetsmanagement," (2000): 189–204.

[274] Langheinrich, "Privacy by Design—Principles of Privacy-aware Ubiquitous Systems," 273–291.

[275] Kargl et al., "Security, Privacy and Legal Issues in pervasive ehealth Monitoring Systems," 296–304.

[276] Ying Cai et al., *Mobile Wireless Middleware, Operating Systems, and Applications* (New York: Springer Publishing, 2010.)

[277] Al Ameen, Liu, and Kwak, "Security and Privacy Issues in Wireless Sensor Networks for Healthcare Applications," 93–101.

[278] Ibid.

The physical level security will include developing systems to protect data or data streams in the system from being tampered with or stolen, but must also include the actual hardware and garments from being accessible. Designers of WST can assist in this by designing tamper resistant garments and systems. Another measure that can be taken is to ensure that only appropriately cleared and approved personnel be permitted to have physical contact with the system hardware or garments while they are in use to decrease the chance of tampering or theft.

Any technical level security will need to take place directly in the hardware, such as the sensors, servers, disks, or other types of devices used both in WST devices and the systems that read and collect information from them.[279] If the network is designed in such a fashion that the data will be sent to central servers, technical security will also need to be used at the server side of the operation. Wireless networks like those in WST garments are very susceptible to hackers.[280] Intrusion detection and prevention methods will need to be in place before a system goes into operation for the data transfers to be made with confidence.

As the Internet of Things (IoT) creates a world populated with "intelligent but invisible data collectors and communication devices, no part of our lives will be able to hide from digitization."[281] It has been suggested that the basic approach that should be taken in regards to the use of ubiquitous computing systems is the "principle of openness, or simply notice."[282] That principle directs that open content or data can be used, modified, and shared by anyone for any purpose.[283]

The EU data protection directive, better known as The Directive, refined and extended the fair information practices by making it no longer sufficient to simply announce that data collection is taking place; it now also requires explicit consent from

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[279] Ibid.

[280] Ibid.

[281] Gregory Abowd et al., *Privacy by Design—Principles of Privacy-Aware Ubiquitous Systems* (Berlin: Springer Berlin Heidelberg, 2001), 273–291.

[282] Langheinrich, "Privacy by Design—Principles of Privacy-aware Ubiquitous Systems."

[283] Ibid.

the subjects whose data is being collected.[284] Written contracts remain the most popular method of gaining a person's unambiguous consent. However, in the modern world of electronic transactions, such overt consent can be difficult to obtain. The American legal system currently views any form of recording without the clear permission of those involved in the recording as "surveillance," which is illegal except in certain law enforcement situations which, in most cases, still requires a court order.[285]

While the EU's Directive elevated the personal privacy protection expectations on businesses who desired to transfer personal information from U.S. to EU companies, the security practices in the United States still operate primarily off the 1974 U.S. Privacy Act and the Fair Information Practices (FIP) it inspired.[286] One of the principles of the FIP is that secret record keeping should not occur. An attitude of openness and transparency was a key to the act. Individual participation expectations meant that any subjects of data collection should be able to see and correct any records kept about them by any organization to whom they have permitted access to personal data. The data that could be collected about any individual person was not permitted to be excessive when compared to the purpose for the collection.[287] The quality of the data was also addressed in the FIP, which stated, "data should only be relevant for the purposes for which they are collected and should be kept up to date."[288] In addition, the information collected may be used exclusively by particular personnel and not be available to the public.[289]

The final practice mandated by the FIP was that record keepers must be accountable for being compliant with all the principles of the U.S. Privacy Act. Despite the laws that exist and the clear mandate by the U.S. Privacy Act, the rapid progress and commercial success of the Internet has challenged the laws and regulations written 40 years ago. "Laws are intended to regulate human behavior" according to David Post, a

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[284] Ibid.

[285] Ibid.

[286] Joel Reidenberg, "Setting Standards for Fair Information Practice in the U.S. Private Sector," *Iowa Law Review*, 1995, 497.

[287] Reidenberg, "Setting Standards for Fair Information Practice in the U.S. Private Sector," 497.

[288] Ibid.

[289] Ibid.

professor at the Beasley School of Law at Temple University, in an article in the *Stanford Law Review*.[290] "The regulation of human behavior takes place through a complex interaction among four forces, four different regulators."[291] Three of these regulators are "law, markets, and social norms."[292] The fourth regulator, according to Post, is "architecture," the united limitations of "physics, nature, and technology" that when combined, define the borders of the places where human behavior occurs.[293]

What makes cyber space and WST a new dimension is that its construction is distinctively defined by code, or "the design of the hardware and software elements that comprise the operations" of this new place.[294] The software and hardware of the Internet and many WSTs create a set of constraints on how a person can function. The makeup of the restrictions will be different between systems, but they are understood as conditions for the WST wearers' access the Internet and all that it permits. In some systems, a password is required to enter into the system, while in others, one is not necessary at all. In some situations, an electronic track is created that links the actions individuals take through "mouse droppings" back to them. The coding, software, and protocols set in the design of WST will constrain behavior by making some behavior possible within the system while limiting or forbidding other behavior. So, while system design has methods through which it can control the availability to breaches and security concerns, the U.S. federal government has taken strides to protect Americans who conduct business on the Internet.

The National Information Infrastructure Act of 1996 established a framework for dealing with computer crimes that may extend to some Internet crimes. The Electronics Communication Privacy Act (ECPA) of 1986 also has application, specifically section s2511 that prohibits "interception and disclosure of wire, oral or electronic

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[290] David G. Post, "What Larry Doesn't Get: Code, Law, and Liberty in Cyberspace," *Stanford Law Review* (2000): 1439–1459.

[291] Ibid.

[292] Ibid.

[293] Ibid.

[294] Ibid.

communication."[295] However, s2511(2)g(i) states, "it shall not be unlawful for any person to intercept or access an electronic communication system that is configured so that electronic communication is accessible to the general public."[296] In other words, information communicated wirelessly may be legally acquired by anyone with the capability to intercept the signal. Wireless systems like WST once again become vulnerable to those seeking to collect, alter, or destroy the communications between the WST garments and the data collection base station. For systems like WST that require wireless communication to transmit sensitive personal health data, end-to-end security will be necessary to meet the demands of the users.

Threats of "tampering with data, DOS, physical tampering and eavesdropping" require more focused security interest in wireless communication networks than they do in other common networks.[297] In technology journals and reports, authors have brought up concerns regarding the "privacy of an individual such as where the health data of a wearer should be stored," and who can view the data.[298] Also concerns have also been raised regarding who will be responsible for maintaining the data and who will be accountable for data security breaches. During an emergency, it may also be in the person's best interest that information be disclosed, which will demand that the system be flexible enough to allow for data to be released without it being so porous that data is easily released or withdrawn without permission.

Data collected by WST networks will be made up of sensitive medical information, and the ownership of that information will not always be clear. It is likely that the fire department will own the sensors and the network devices, while the data being collected belongs to the wearer. Further, data must be available during emergencies to ensure proper care is given, but access must not leave an electronic trail that can lead to abuses and system vulnerability. To aid in protecting the information collected by WST systems, "proper encryption and authentication mechanisms" will be necessary to

[295] Kargl et al., "Security, Privacy and Legal Issues in Pervasive ehealth," 296–304.

[296] Ibid.

[297] Ibid.

[298] Langheinrich, "Privacy by Design—Principles of Privacy-aware Ubiquitous Systems," 273–291.

help guarantee the security of the information transmitted.[299] Although it is important that all existing laws and codes of practice be considered, it is equally critical to recall that legal mandates can only succeed when properly teamed with the social and technical capabilities permitted by the realities of the system.[300] As a result, it will be necessary to bring together specialist from the various fields involved including the medical, legal, and insurance fields to discuss various aspects of modern communication technologies to ensure that the population can fully embrace the potential available from this technology.

2. Medical Information Privacy

In 1996, the HIPAA was made public law.[301] HIPAA required the Department of Health and Human Services to adopt "a national standard for electronic health care transactions and code sets," as well as to establish regulations related to the security of medical data.[302] This law resulted in comprehensive changes to the portability of health insurance information and established privacy rules to safeguard protected health information (PHI) and/or electronic personal health information (ePHI). The primary components of the HIPAA law can be broken down into three general rules: the privacy rule, the security rule, and the breach notification rule.[303]

The HIPAA privacy rule created a new set of laws created to establish a national standard to ensure that all medical records and personal health information were protected. HIPAA compliance is only required for "the protection of individually identifiable health information by three types of covered entities: health plans, healthcare clearinghouses, and those health care providers that perform health care transactions electronically."[304] The privacy rule dictates that appropriate barriers be put in place to guarantee the security of personal medical data, as well as to set limits and boundaries on

[299] Marci Meingast, Tanya Roosta, and Shankar Sastry, "Security And Privacy Issues with Health Care Information Technology," *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*, 2006, doi:10.1109/iembs.2006.260060.

[300] Langheinrich, "Privacy by Design—Principles of Privacy-aware Ubiquitous Systems," 273–291.

[301] "Combined Regulation Text of All Rules."

[302] "Combined Regulation Text of All Rules."

[303] Ibid.

[304] Ibid.

acceptable "uses and disclosures" that can be made regarding the protected information without the consent of the patient.[305] In addition, the privacy rule gives patients the legal right to access their own medical records, which includes the right to "examine, obtain copies of, and request corrections to their own health records."[306] The HIPAA law was made more important with the passing of The Health Information Technology for Economic and Clinical Health (HITECH) Act, which was signed into law on February 17, 2009.[307] HITECH was enacted as part of the "American Recovery and Reinvestment Act."[308] Its purpose was to encourage the implementation and meaningful use of health information technology through the use of electronic health records (EHS).[309]

Questions regarding the applicability of HIPAA laws for fire department employees as they relate to wearing of WST have varying answers depending on multiple specific operational and administrative considerations. If a fire department provides medical care as part of its service, it is mandated to comply with all HIPAA laws for the patients it treats. In that case, the answer to whether their employees' PHI and/or ePHI must be kept secure is made clear by the definitions of the terms in the HIPAA law.

According to the Department of Health and Human Services HIPPA law, a "participant" means an employee or former employee who is or may become eligible to receive a benefit from a(n) (insurance) plan.[310] This definition is the baseline for the determination that fire departments' employees' health information must be handled in compliance with HIPAA rules and regulations. However, if a fire department does not provide medical care as part of its service, then it may not be required to be HIPAA compliant, and thus, its employees PHI and/or ePHI may not be mandated to be HIPAA protected.

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305 Ibid.

306 Todd Fitzgerald, "The HIPAA Final Rule: What's Changed?," *Information Systems Security* 12, no. 2 (2003): 50–59, doi:10.1201/1086/43326.12.2.20030501/42587.9.

307 David Blumenthal, "Launching HIteCH," *New England Journal of Medicine* 362, no. 5 (2010): 382–385.

308 Ibid.

309 Ibid.

310 "Combined Regulation Text of All Rules."

The HIPAA security rule created a national standard for the protection of individuals' ePHI that is created, received, used, or maintained by healthcare clearinghouses, and health care providers that perform health care transactions electronically.[311] As part of the security rule, it became mandatory that all HIPAA qualifying agencies create appropriate "administrative," "physical," and "technical" protective measures to guarantee "the confidentiality, integrity, and security of all ePHI."[312] By the definition given in the HIPAA law, PHI and ePHI are individually identifiable health information maintained or transmitted in any form by any entity covered by HIPAA.[313] According to HIPAA, PHI and/or ePHI may not be used or revealed except when: "a) the individual who is the subject of the information has authorized its disclosure, b) the individual who is the subject of the information agrees or does not object to the disclosure and the disclosure is to persons involved in the health care of the individual."[314]

To be able to use WST in the fire service without risking violations of the variables that determine HIPAA compliance or non-compliance, the use of waivers by the firefighters would be required to put them in compliance with section (a) of the exemption rule. A waiver signed upon hiring that PHI will be recovered for the purpose of health monitoring while in active firefighting operations, may release the fire department from the mandate to make every effort to maintain the security and privacy of the employees PHI and/or ePHI. Additionally, as was discussed in the privacy and security section of this document, numerous technical safeguards can be put in place to assist in protecting PHI and/or ePHI while WST are in use.

The HIPAA breach notification rule demands all HIPAA mandated agencies and their partners must give notice to all affected individuals after an infringement takes place

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[311] Ibid.

[312] Young B. Choi et al., "Challenges Associated With Privacy in Health Care Industry: Implementation of HIPAA and the Security Rules," *J Med Syst* 30, no. 1 (2006): 57–64.

[313] "Combined Regulation Text of All Rules."

[314] Joan Hash, "An Introductory Resource Guide for Implementing the Health Insurance Portability and Accountability Act (HIPAA) Security Rule" (PhD diss., National Institute of Standards and Technology, 2005).

involving unsecured PHI or ePHI. Following the discovery of a breach, the individuals affected by the breach must receive notification as quickly as possible and notification is never permitted to exceed 60 days. As part of the notification, the affected individuals must be provided, "a brief description of the breach, a description of the types of information that were involved in the breach," and "the steps affected individuals should take to protect themselves from potential harm."[315] Also, a "brief description of what the covered entity is doing to investigate the breach, mitigate the harm, and prevent further breaches, as well as contact information for the covered entity" must be provided.[316] In some cases, individual states have established stricter timelines for breach notification. In those cases, the stricter timeline will be the enforced standard.

3. Union Considerations

A major concern for all career and combination fire departments (career and volunteer mixed) is the influence of the professional firefighters union. For most fire departments in the United States, the IAFF is their union organization.[317] The IAFF represents more than 300,000 professional firefighters across the United States and Canada in over 3,100 locals.[318] These professional firefighters account for the protection of over 85% of the population in the United States and Canada.[319] As a result, the influence and power of the IAFF is substantial within the fire service. Although the stated purpose of the union is to focus specifically on issues related to pensions, collective bargaining, health care, staffing, occupational safety, compensation, and presumptive protections, they have often been brought in to fight for or fight against changes to the services fire departments will provide, or the methodology with which services will be provided.

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[315] Ibid.

[316] "Combined Regulation Text of All Rules."

[317] "Welcome to the IAFF website," accessed May 22, 2015, http://client.prod.iaff.org/#page=AboutUs.

[318] Ibid.

[319] Ibid.

The IAFF leadership has made it clear in its publications that they support the use of technological advancements that have a proven benefit towards their stated goal of improving firefighter cardiac health and decreasing firefighter loss of life.[320] In previous labor/management issues that involved the security and transmission of personal medical information, the union leadership has taken a stance that clear and conscious language in contracts was sufficient provided it addressed the aftermath of data collection. This language would be important specifically for cases where underlying cardiac or medical conditions are revealed by WST that are not acute life threatening issues, but are issues that need to be addressed by a physician. In these cases, the proper wording in the contract would serve to protect the firefighters' job, while also ensure that the firefighter is not permitted to continue working until they have been cleared to return to work by a physician.

4. Start-up, Acquisition and Maintenance

The start-up and acquisition costs of WST for use in the fire service will depend greatly on the style of garment selected and the number of different sensing capabilities within the system procured. Prices will be affected by system specific components, such as communication systems and capabilities, battery life, and system functionality. While the prices of WST are currently very expensive, that scenario may quickly change when production of these garments transitions into large-scale production. However, at this time, garments on the upper end of sensing capabilities are running $5,000–5,200 dollars per garment.[321] While that cost includes all the necessary components for a single wearable sensor garment including battery, communication capabilities, and sensors, it does not include the hardware and software for the receiving side of the system. Those components will result in an additional expense that will increase costs another $4,000–5,000 per receiving station.

[320] Marilyn Ridenour, *NIOSH Fire Fighter Fatality Investigation and Prevention Program* (Cincinnati, OH: Dept. of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 2008).

[321] ProeTEX and the European Commission, *D1.1 Report of Requirements, Protection E-Textiles: Micronanostructured Fibre Systems for Emergency-Disaster Wear* (Pavia, Italy: Eucentre, 2006). Not available for public access. Permission to use this document was granted by author to this researcher.

For WST in the fire service, a support structure will need to be established that will result in costs associated with securing a contract with an information technology (IT) company or with a municipal entities IT department. The costs of such contracts will vary significantly based on the number of garments in use by the department, the number of receiving stations the department establishes, and any pre-existing contracts that may exist between the fire department and the IT service provider. Further system support will need to come in the form of garment maintenance to include making any necessary repairs in the event of rips or tears in the garment material and laundering services. Another component of start-up and acquisition would be the establishment of a repair and replacement schedule.[322] Due to the costs of each garment, a budget would need to be created that would establish a replacement schedule for the garments themselves based on estimated life spans of the garments while accounting for the unexpected immediate replacement needs for "off-schedule" garment failures or replacement demands.

Cost consideration must extend beyond the start-up and acquisition costs and also consider the costs of maintaining the status quo and having to accept the costs associated with a firefighter's LODD. Although this section focuses primarily on the financial aspects of a LODD, much more is at stake than the fiscal effects of a firefighter's LODD. The death of a firefighter has been seen to result in a degree of loss of public confidence in the fire department, which can affect future budgeting, job security, and have political repercussions outside the fire department.[323] The financial repercussions of a firefighter's LODD can be extremely substantial. Very few fire departments have budgeted with consideration of being prepared to cover the expenses related to a firefighter on duty fatality. Another issue that must be considered is where the financial ripple effect of a LODD extends. In almost all cases, it goes well beyond the fire department and includes the community, the taxpayer, the insurance companies, the state, the federal government, and the family of the firefighter who died.

[322] State of Texas Legislative Budget Board, *Review of Replacement Schedules for Information Technology Equipment* (Austin, TX: Department of Information Resources, 2013).

[323] U.S. Fire Administration, *Special Report: The Aftermath of Firefighter Fatality Incidents—Preparing for the Worst* (Emmitsburg, MD: Department of Homeland Security, 1998).

The financial costs of a firefighter's LODD may be measured as either direct or indirect costs. Direct costs may include the replacement costs for lost or damaged equipment or apparatus, accrued sick leave expense and overtime expenses for relief, funeral expenses (typically several thousand dollars), the cost of reception and memorial services, and many others related to the incident and its investigation. The indirect costs can be built out to extremes, and at some point, become incalculable. However, indirect costs often include additional staffing sent to the fire ground as a support team for the incident and its responders, administrative costs for insurance, and union costs for planning and supporting the funeral activities. Table 2 has a layout of direct and indirect costs associated with a LODD.

Table 2. Layout of Direct and Indirect Costs Associated with a LODD

Type of Cost	Discussion
Direct	
Workplace	
Backfilling	Cost of personnel to replace firefighter killed.
Lost Productivity	Cost required due to inability to perform required functions because replacement workers are not as skilled as deceased firefighter or because worker's effectiveness was diminished following the firefighter fatality.
Administration	
Legal Fees	Lawyer fees to defend personal injury and death lawsuits brought by firefighters or dependents and to prosecute against claims decisions to include legal fees, court costs, and settlements/judgments excluding punitive damages, and pain and suffering.
Paperwork and Data Collection	Cost of personnel time and systems used in filing reports of injury, claims for compensation, insurance forms, collecting information, etc.
Investigations	Time, expenses, and materials associated with investigating and documenting incidents and claims.

Type of Cost	Discussion
Insurance	
Non-Medical Payouts	Wage differential payouts made by insurance coverage on death and disability coverage.
Premium Increases	Increase in insurance premiums.
Medical Expenses	
In-patient Care	Costs directly related to any hospitalization for medical services, including emergent transport and care from the prehospital environment.
Federal Payments	
Public Safety Officers Benefit Program	Cost of federal payments under the Public Safety Officers Benefit law. These are made for disabling injuries and fatalities.
Lost Income	
Career	Difference between regular wages and those paid under death and disability status.
Second Jobs	Loss of wages from any additional source of income.
Caregiver	Loss of wages for any caregiver forced to reduce/terminate employment due to death of firefighter.
Indirect	
Insurance	
Administrative Costs	Costs related to the administration of insurance, which does not include indemnity or medical payouts.
Prevention	
Personal Protective Equipment	Costs of equipment, including maintenance and upgrades.
Other Direct Costs	
Pain and Suffering	Intangible costs and consequences of changes in the lives of the family or the deceased firefighter.

It is not possible to put an absolute value on a firefighter's life; thus, some allowances must be made for costs of a firefighter on duty death. However, based on a study of firefighter injuries, it was seen that a firefighter injury that does not result in death still may have a total cost of over $215,000.[324] Those expenses, although substantial, do not include the many additional costs associated with a fatality. Following the LODD of a firefighter, the local government and fire department will need to be prepared to fund life insurance for the survivors of that family as mandated by the federal COBRA law for a period not to exceed 36 months.[325] They will also have to pay for retirement, final paycheck, sick leave payout, vacation leave payout, and coverage of any hospital/emergency transport costs.[326] State government must fund the state line-of-duty death benefits, workers compensation, funeral burial allowance, retirement/pension, health insurance in many states, and educational assistance for the surviving dependents of the firefighter, as well as the spouse.[327]

The Public Safety Officers' Education Assistance (PSOEA) Program provides financial assistance through the U.S. Department of Justice, Bureau of Justice Assistance. It provides a maximum of $881 a month to cover educational expenses.[328] Beyond that amount, many states have passed laws that ensure that the dependents of a firefighter killed in the line-of-duty will be admitted to and receive free room, board, and education at any state college within that state.[329] Another federal program that must pay following the death of a firefighter in the line-of-duty is The Public Safety Officers' Benefit (PSOB) Act (42 U.S.C. 3796), which provides a one-time cash payout for eligible survivors. This payout as of October 2013 was $333,604.[330]

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[324] GCR, NIST, *The Economic Consequences of Firefighter Injuries and Their Prevention*, Final Report (Arlington, VA: National Institute of Standards and Technology), 2005.

[325] National Fallen Firefighters Foundation, *Line-of-Duty Death Benefits Guide—A Handbook for Survivors of Fallen Firefighters* (Emmitsburg, MD: National Fallen Firefighters Foundation, 2008).

[326] National Fallen Firefighters Foundation, *Line-of-Duty Death Benefits Guide—A Handbook for Survivors of Fallen Firefighters*.

[327] Ibid.

[328] U.S. Fire Administration, *Special Report: The Aftermath of Firefighter Fatality Incidents—Preparing for the Worst*.

[329] National Fallen Firefighters Foundation, *Line-of-Duty Death Benefits Guide—A Handbook for Survivors of Fallen Firefighters*.

[330] National Fallen Firefighters Foundation, *Line-of-Duty Death Benefits Guide* (Emmitsburg, MD: National Fallen Firefighters Foundation, 2013), 16–32.

While the immediate costs of implementing a WST system seem steep, they must be balanced against the costs of not implementing a program that can reduce the likelihood of needing to pay for the costs associated with a firefighter's death.

5. Training

Training should be required for all department personnel who may use or otherwise be involved with the WST systems. This training should include all firefighters and fire officers, supervisors whose crews will be using the garments, and training staff members. Training should focus on practice and policies that involve the WST systems including how to document and report garment or system malfunctions or damage, procedures for operating the systems components safely and effectively, and include scenario-based exercises that replicate situations that will require the use of WST by firefighters.

Supervisors and those who will be exposed to the receiving end of the communications loop of this technology will need to receive training on procedures for responding to system alarms, policies for firefighter withdrawal if the system detects physiological abnormalities, and procedures for accessing and reviewing the data being received from the field worn WST garments. Training at the supervisors level will also need to address the legal considerations of who can delete the data received, when it can be deleted after an incident, and who shall have access to the data prior to its disposal.

This training will require a substantial investment of training hours that will detract from the available time to complete other mandated training. As a result, legally required training will have to be performed during other periods, which may result in fire departments needing to fund overtime (OT) expenses. Supervisors will have a particularly significant training demand placed upon them due to their need to understand and be able to operate both sides of the WST system. After the initial training cycle is complete, quarterly updates and annual refresher training will easily dovetail into existing training packages resulting in the original costs of the start-up training being a one-time expense.

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V. CONCLUSIONS

The American firefighter is frequently referred to as "America's bravest." Firefighters' willingness to go into harm's way to save a human life, or put themselves in danger to protect another's property has made that unofficial title well deserved. However, despite the bravery firefighters across the nation demonstrate each and every day, over 100 firefighters will die this year, just as they have for the last 30 years. The LODD death rate for the American firefighter remains unchanged despite the decrease in structure fires being fought, as well as the initiation of numerous programs that have targeted firefighter health and safety. Firefighters die in the line-of-duty for many reasons, which makes the possibility of a zero firefighter death a near impossibility. However, the leading cause of firefighter deaths has been well established to be heart attacks and/or cardiac arrest related to the exacerbation of underlying CHD.

Firefighters share the same risk factors for CHD as does the general public, which includes poor diet, hypertension, lack of exercise, and stress. However, what is less known is that firefighters, as a result of their profession, are exposed to additional factors that substantially increase their risk of CHD and sudden cardiac arrest. Some of those additional factors are the strenuous physical nature of the work performed by firefighters, the heat stress that is ever presence on the fire ground, as well as dehydration that often accompanies the work of firefighting.

Prolonged episodes of sympathetic nervous system activation and numerous different psychological and sensory system assaults are also components that take a toll on firefighters who already suffer from underlying CHD. Programs, such as *NFPA 1500, Fire Department Occupational Safety and Health Program, NFPA 1582, Standard on Comprehensive Occupational Medical Program for Fire Departments, NFPA 1583, Standard on Health-related Fitness Programs for Fire Fighters* and the IAFF/IAFC's *The Fire Service Joint Labor Management Wellness-Fitness Initiative*, have all failed to reduce the number of firefighters dying in the line-of-duty, despite their positive objectives.

The development of "smart clothing," advancements in the miniaturization of technology, and improvements in the wireless communication fields have come together for the creation of a tool that could greatly reduce the number of firefighters who die from cardiac related events while operating on the fire ground. WST is the combining of a comfortable fabric with physiological sensing capabilities that allow for the continuous observation of the wearers' vital signs from distant locations. Although the sensing capabilities of the garments differ from one design concept to another, all WST being marketed for the fire service allow for the monitoring of the wearers' HR, RR, SpO2, and EKG/ECG. These four vital measurements of wearers' physiological functioning are enough to allow an observer (generally the IC or respective aide) at the receiving end of the data stream being created by the WST to detect any changes in vital signs or EKG to initiate a timely medical intervention on the wearers' behalf. As has been proven in numerous studies by the American Heart Association and the American College of Cardiology, the faster the recognition is made of a heart attack through a 12-lead EKG, the faster the treatment can begin and the better the survivability rates both in the short-term and long-term.

Although the use of WST is not aimed at decreasing the number of heart attacks suffered by firefighters while operating at fire scenes, it has demonstrated a clear value in recognizing those who do suffer a cardiac event and may allow for a much more prompt response by medical professionals. Once in the care of the on-scene paramedics, rapid assessment including a 12-lead EKG will permit quicker initiation of pharmacological care that will exceed the national standards for ideal door-to-drug time. This rapid assessment, diagnosis, and initiation of cardiac treatment will result in less firefighters dying and allow for more firefighters who do suffer a cardiac event on duty to come back to their departments healthy and ready to serve their communities.

A. FINAL ASSESSMENT AND DETERMINATION OF WST FOR THE FIRE SERVICE

After assessing and analyzing the four WST systems, a determination based on that research is that the ProeTEX system is currently the best system available for use in the fire service. As illustrated in Table 2, the ProeTEX system has been consciously designed to be exceptionally wearable, with minimal additional weight for the wearers, a comfortable design, easy to don and doff, easy to remove in the event of an emergency, while not limiting the wearers' ROM. The durability of the ProeTEX system was an intentional design based on the knowledge that its technology was being made specifically for the fire service. As a result, the ProeTEX components have been made to resist rips and tears, moisture, and heat. In much the same way as ProeTEX was designed to be durable, it was also made to be easy to maintain through its easy of washing, easy of battery charging, and ease of software upgrading that will improve the long-term use of the system.

Perhaps the most critical component of the WST is its functionality. Like all the other systems, ProeTEX is able to deliver the wearers' HR, RR, SpO2, and give a temperature reading, but it has many additional capabilities that make it stand out. ProeTEX's ability to monitor external variables, such as hazardous gas levels and oxygen deficient environments, is a unique feature, shared only by the GTWM. However, unlike the GTWM the ProeTEX system measures a true respiratory rate based on thorax expansion rather than an estimated respiratory rate based on SpO2 readings, which do not reflect active breathing but rather estimates breathing rates. While the VTAMN and MagIC both also have true respiratory rate measurements, both systems fail to deliver in other areas, such as wearability or durability.

Additionally, ProeTEX is also able to detect falls and measure the absolute speed and position of the wearer, which has applications beyond the scope of this thesis. While ProeTEX is the most expensive of the systems whose prices are known, a great deal of the expense results from ProeTEX being an entire firefighting ensemble and not just a shirt worn under the firefighters' current bunker gear. As fire departments are mandated to replace firefighters' protective ensembles every 10 years, the additional cost of procuring the ProeTEX system with its complete bunker gear design negates a substantial portion of the cost difference.

B. RECOMMENDATIONS AND EXPECTATIONS

It is recommended that the American fire service explore the implementation of WST as a mandatory piece of safety equipment for all structural firefighters in the United States. Upon completion of testing and certification by organizations, such as OSHA, UL, and NFPA, fire departments should be given a mandate to provide WST garments to all firefighters regardless of career or volunteer status, as well as initial training, quarterly training, and annual recertification training. In addition, all fire departments should be mandated to ensure that IC and/or respective designee will monitor the WST receiving station for the duration of firefighting operations.

C. UNKNOWNS AND LIMITATIONS

Despite the significant amount of research that has gone into the development and refinement of WST, a few unknowns remain related to the acceptability and feasibility of its use within the fire service. The first unknown that remains is the willingness of the fire service to adopt such a change.

The culture of the fire service will offer significant resistance to the implementation of WST. This culture is one that has developed a resistance to change, and expects full involvement in the planning and researching of any potential change that may affect its routine or emergency operations. The NFFF has stated that “the culture of the fire service is a major contributor to the fatal trend in the fire service.”[331] It is also recognized that “some type of cultural change is needed to change the perceptions of acceptable and unacceptable risks.”[332] When asked about the dangerous behaviors they undertake, firefighters will often state that there are both organizational and public expectations require them to act as they do and to place their own lives and health second to that of those they serve. These beliefs and behaviors comply with the image that

[331] U.S. Fire Administration, *National Safety Culture Change Initiative* (FA-342) (Emmitsburg, MD: Federal Emergency Management Administration, 2015).

[332] Ibid.

firefighters have earned and now try propagate as being the selfless American heroes who willingly puts their lives on the line "to save the life of a total stranger and who is lauded for doing so."[333]

The fire service takes great pride in its culture, and for many, their fire department is defined by its culture. This culture includes the use of "a uniform hierarchical command structure, promotion solely from within the existing ranks, and many long-standing traditions."[334] In some cases, these traditions are taught as solutions to problems that ignore the fact that they are incorrect practices. Despite the fact that these methods are recognized as being incorrect, their use continues as a department or fire service tradition.

The term "culture" in its most basic form simply describes how things are done within an organization.[335] This definition may help to illuminate just how interwoven the fire services operational capabilities and delivery methodologies are with the culture within which the fire service operates. The culture of the fire services is driven by its "organizational history, policies, uniforming, facilities, vocabulary, leadership and management within the organization."[336] The culture that exists within the fire service has developed through years of passed down stories and shared experiences, as well as being acquired at training exercises, emergency incidents, and around the dinner table. It is through this process that the culture of the fire service has been formed, and it is through this process that the culture must change for the implementation of WST to be accepted.

As a "service-focused" organization, the fire service would be fine in having a well-defined identity and presence in the communities it serves, as well as being willing to take risks to carry out its calling. However, these traits are only acceptable when they exist in an environment in which safety is the constant driving force. Too often, however,

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[333] U.S. Fire Administration, *National Safety Culture Change Initiative*.

[334] Ibid.

[335] D. Compton, "Leadership for Today and Tomorrow," in *The Fire Chief's Handbook* (2003): 205–228.

[336] Ibid.

the fire service culture is less focused on safety and more focused on retaining its “hero” image, prepared to risk the lives of its members while carrying out its duties. This emphasis on meeting the perceived cultural expectations of the community is reflected in LODDs, which are treated as heroic regardless of the nature and causes behind the death.[337]

Recognizing that the culture of the fire service is a major contributor in the consistently high numbers of firefighter fatalities is not a recent development. The IAFC, IAFF, and the National Fallen Firefighters Foundation (NFFF) have identified culture as a crucial area that is impeding a revolution of thinking and acting with a safety first attitude within the fire service. Some of this cultural resistance comes from the strong unions that are a major component of the fire service culture. Changes that are mandated from department administration, such as the chief or assistant chief, are often meet with legal challenges and battled through contract negotiations regardless of the safety improvements that the change might have within the fire service. Related to the strong union presence within the fire service, close budgetary monitoring by firefighters of their departments leaders will create another challenge to the implementation of WST in the American fire service. Many firefighters or their union leaders will want to know what else could have been purchased, which has proven safety applications, and which do not risk invasion of personal privacy of the members.

While the current culture within the fire service does not seem ready for the introduction of WST, a change is taking place across the country. In March 2004 at the Firefighter Life Safety Summit in Tampa, Florida, the first of 16 firefighter life safety initiatives was written that reads, “Define and advocate the need for a cultural change with the fire service relating to safety, incorporating leadership, management, supervision, accountability and personal responsibility.” This initiative, although slow in its initiation, has begun to take root in many individual departments and specific regions.

Changes in the values of the fire service have legitimized and encouraged further variance in behavior. The changes in behavior then must be reinforced and rewarded by a

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[337] U.S. Fire Administration, *National Safety Culture Change Initiative*.

continuous dedication to the development and advancement of a safety minded organization that can only be achieved, as it always has been, through training, emergency responses, proper use of downtime around the station, and during informal activities. A change of culture "can only be accomplished by convincing the firefighters at every level that change is both desirable and necessary, and that adjustments may be accommodated without compromising any of the highly valued aspects of the fire service culture."[338] Through this process, the "hero" culture of the fire service can slowly be replaced by a culture of intelligent strategy and strategic actions based on on-going risk and reward assessments of the situation.

The second unknown that remains for the implementation of WST in the fire service is the system limitations for data reception. While studies of systems like ProeTEX have performed well with individual or small group data streams, trials have not been performed where large numbers of firefighters were simultaneously transmitting their data to a single receiving station. To ensure that the system selected for fire service use is able to handle large amounts of data, trials will need to be performed where receiving stations are required to receive large amounts of data simultaneously. Receiving stations should be taxed to the point of failure to see what the results of such a collapse would be, as well as to assist in designing emergency actions to take by the receiving station attendant in the event of such a failure.

A significant limitation to WST capabilities is the lack of a consistent and reliable GPS capability for structural firefighters. Due to the nature of structural firefighting, most operations take place within the confines of walled and covered structures. As a result, the GPS signals from most WST systems are not able to transmit to the satellites needed to pinpoint the wearers' exact location. This capability, although not a critical component of the system, is a potentially significant benefit to the firefighters wearing the garment, as well as the citizenry who are relying on the firefighters to perform their job with peak efficiency. As technology continues to improve, the author is hopeful that a resolution to

[338] Compton, "Leadership for Today and Tomorrow," 205–228.

this current limitation can be resolved to allow for the full potential of WST to be achieved.

D. FUTURE RESEARCH

This thesis and its expectations are based on estimations, correlations, and best evidence. Should WST be adopted, a performance matrix will need be established based on reporting and incident data collection. System successes and failures will need to be collected by the fire service and not just the manufacturers of the garments. Data collection, to be accurate, will need to be performed at a national level from departments of all sizes, composition, and locations. The data will need to assess the accuracy and reliable of the system and its individual components, as well as any unintended consequences of its usage.

Additional research into WST should explore the use of this technology in the fire service beyond the fire ground to include the value it may have in training and during response times when firefighters are driving to and returning from emergency incidents. Research should also explore beyond the fire service to find applications for this technology in other fields. This research may focus on WST for monitoring of astronauts during their missions, as well as for deep sea divers who spend long durations submerged breathing gases in concentrations different than those found in the atmosphere.

The potential uses for WST are numerous, and research into its many applications is limited only by the imagination of the designers and academics who choose to explore its potential.

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