Strategic Physiological Alert System (SPAS)

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Introduction

The modern battlefield, whether it be land or sea, is riddled with sensors and intelligent systems to analyze and optimize a wide range of systems from combat systems to communication systems. Yet the military's most valuable system, the warfighter, is not analyzed in the same objective manner. Instead, the warfighter is chronically fatigued from lack of sleep, food, and recovery time while working in high stress situations. Dangerous operating environments and the relentless physical and cognitive abuse Warfighters face while deployed dramatically increase the risk of injury and chance of mission failure. It is not uncommon for a Warfighter to deal with an injury for hours or days in order to complete the mission. While completing the mission is important, many injuries are preventable with proper real-time monitoring and operational decision support. Proactively predicting injuries and performance decrement will enable mission success more than reactive treatment during the mission. Predicting injuries can contribute to mission success by allowing leadership to plan personnel and/or mission start time and/or duration to reduce the likelihood of preventable injuries and, by extension, mission failure. Advancements in wearable technology and intelligent systems allow the Warfighter to be supported and optimized just as any other high performing system.

Wearable technology is able to monitor physiological signals such as heart rate (HR), heart rate variability (HRV), temperature, blood volume pulse (BVP), respiration rate (RR), galvanic skin conductance (GSR), motion via 3-axis accelerometer, etc. However, there is not currently a method to translate these physiological measures into physical states of the Warfighter such as injured, fatigued, sleep deprived, etc. The goal and benefit of this information is to provide objective feedback on past, current, and predicted future physical states of the individual to detect physiological episodes (PE) or predict when Warfighters are at higher risk of PE. Retroactive data analysis introduces a new methodology for individualized performance training and evaluation while current and predicted future performance data can be used to make a tactical adjustment during planning or execution of a mission. Professional sports teams are actively adjusting training, eating, therapy, and sleep schedules to optimize recovery and increase performance during games. Coaches and trainers are notified instantly when an athlete is at risk of injury or has already been injured. These commercial systems, however, are not suitable for many military environments and need to be customized to address specific military needs. The military has the opportunity to develop and harness similar techniques to deliver a real-time decision aid and mission planner based on physical health of the Warfighters, ultimately created a more effective military.

Background

The Naval Surface Warfare Center Dahlgren Division (NSWCDD) Human Performance and Augmented Warfighter team developed a machine learning algorithm to detect cognitive fatigue using physiological signals collected from a wrist-worn device funded by Naval Innovative Science and Engineering (NISE-219), titled *Fatigue Detection/Prediction Using Machine Learning and Wearable Technology* in Fiscal Year 2020. The team developed and executed a human research study (IRB Protocol Number: NSWCD.2019.0001-AM01-EP4-A) to build a data set of participants completing tasking

designed to cause them to slip into a cognitively fatigued state while wearing various wearable devices that captured physiological data. The 2-Dimensional Convolutional Neural Network (CNN) developed was trained on a data set of 30 participants and is able to detect task performance accuracy within 2.5% using only HR, GSR, temperature, accelerometer, and BVP collected from a wrist-worn device. Additionally, another CNN was developed to classify if the operator was in a state of high or low cognitive load.

Further, the NSWCDD Expeditionary Systems Integration Branch (H14) Expeditionary Medicine (ExpMed) Team, supported the Marine Corps Systems Command (MCSC), Program Manager for Supply and Maintenance Systems (PM-SMS), Expeditionary Medical Systems (EMS) with the validation of the Forward Resuscitative Surgical System (FRSS) nine-patient configuration at a field user evaluation (FUE) in December 2020. One of the key questions that came out of the study was whether the FRSS eight-person team met the stated requirement of providing Damage Control Surgery (DCS) for nine casualties over a 48-hour period. From the 2019 FRSS study, it was identified that fatigue could play a role in delivery of this capability over the required (as cited in current Statement of Need) 48-hour period. To test the hypothesis, each member of the eight-person FRSS team (general surgeons, anesthesiologist, critical care nurse, medical technicians) was outfitted with a wrist-worn device to collect physiological signals throughout the entire exercise. The exercise consisted of treating nine simulated casualties requiring DCS as they would in theater. Once the casualty was deemed to be stabilized, each member performed a series of cognitive tests to determine current level of fatigue and performance decrements related to response time, likelihood to accept risk, and decision making. In addition to answering the fatigue question, the NSWCDD ExpMed Team and Human Performance and Augmented Warfighter Team are collaborating to apply of the FUE data to further mature the fatigue detection/prediction algorithm for application in future medical team planning, especially for DCS team rotation, as part of implementing the USMC Force Design 2030 plan.

Approach

NSWC Dahlgren's Human Performance and Augmented Warfighter Team is proposing to develop and integrate a decision aid system of wearable devices to detect and alert team leads and corpsman/medics when a Warfighter's physiological signals show signs of PE. The team will enhance and adapt current algorithms, wearable systems, and testing protocols to address the PEs specified in the Request for Project Proposals (RPP). A proposed list of PEs to be detected will be drafted and presented to sponsor for feedback and finalization. To reduce the risk of injury, the system will track activity and detect when the Warfighter is showing signs of reduced performance, which can be an indicator of experiencing a PE. All metrics will be collected locally on the wearable device and shared to a platform operated by the team leads and corpsman/medics. The platform will inform the team lead and corpsman/medic if/when a team member's performance is degrading to a point where they risk injury to self or others and/or showing physiological signs of a PE. Devices will require a training period of approximately two weeks for the algorithm to build a "normal" for the individual.

The proposed effort will utilize the same methodology for fatigue detection and prediction and apply it to the prediction of PE from wearable sensors. This effort will be completed in two phases: development of a single-person alert system and extending the single-person alert system to support

multiple persons. The first phase will take approximately 16 months. In this phase, the major tasks to be completed are:

1. Comparing and selecting commercially available wearable devices
2. Analyzing relevant and available medical data sets or creating a data set
3. Training a machine learning algorithm that can detect a narrowed set of PEs (hyperventilation, anxiety, and physical fatigue)
4. Designing, building, and testing a software application to alert when the wearable device detects the performance decrement. This step will include operational validation of prototype system.

The team previously worked with physiological signals related to hyperventilation, anxiety, and physical fatigue and has confidence that these three PEs have the simplest solutions. In Phase One, several potential research avenues will be investigated and results will be used to determine next steps. These approaches can be classified into two primary categories. One will focus on unsupervised learning techniques to identify outlier events, anomalies, and multi-dimensional data inflection points and change points from publicly available raw unlabeled/un-annotated bio-signals data sets and clinical data bases. The other approach(es) will attempt to leverage the growing number of publicly available annotated clinical bio signal data sets, and implement supervised Deep Learning (DL) models for event classification and predictions.

Supervised Learning Approach

In recent years, a number of large bio-signal data sets have been curated, annotated with physiological event and clinical metadata, and made publicly available. One of the most notable of these data sets include The Medical Information Mart for Intensive Care (MIMIC) clinical and waveform databases. The MIMIC III Waveform Database contains 67,830 record sets for approximately 30,000 Intensive Care Unit (ICU) patients. Most of these recorded sets contain digitized signals (typically including ECG, ABP, respiration, etc.) containing semi-continuous time series of periodic measurements for patients through their stay in the ICU. More importantly, a large subset of this wave form data has been matched and time-aligned with 10,282 MIMIC-III Clinical Database subjects. This Clinical Database provides vital signs, medications, laboratory measurements, observations, notes charted by care providers, procedures, and diagnostic codes that can be treated as data annotations for the waveform sets. Other notable annotated data sets include responses to the Valsalva maneuver, wearable device data sets, and electrocardiogram (ECG) data with manually annotated P-wave and T-wave peaks, among many others. A full list of curated, and annotated data sets can be found at the PhysioNet website (https://physionet.org/).

Most of these annotated data sets are in the form of digitized time-series and there are a number of DL models that have, in the literature, demonstrated state-of-the-art performance in time series classification and prediction, sequence to sequence mapping, and rare event detection on annotated data sets. These include Recurrent Neural Networks such as Long Short Term Memory (LSTM) and Gated Recurrent Unit (GRU) models, as well as more recent ML architectures such as Attention and Transformer models. Assuming that these datasets are annotated with physiological events that are of specific interest, the above models will be developed and trained to detect and predict these events. It is worth noting that researcher associated with the

NSWCDD Human Performance and Augmented Warfighter team have successfully developed and trained LSTM, CNN and Attention models for a variety time series prediction and classification tasks using physiological signals.

Unsupervised Learning Approach

In the cases where a data set annotated with a specific physiological event of interest cannot be identified, unsupervised learning techniques can be utilized. Here the relevant medical literature will be thoroughly reviewed in order to identify known correlations between specific physiological events of interest and specific signal features. Statistical analyses, spectral decomposition and signal processing, and unsupervised manifold learning techniques can then be used to search both for known signal features, as well as anomalies and change/inflection points in the multivariate data. These techniques may include commonly used clustering, k-nearest neighbor techniques, isolation forests, as well as the less ubiquitous high order statistics (HOS) (e.g. 3^{rd} and 4^{th} moments and cumulants) which have been successfully used for anomaly detection on very high dimensional datasets. Once the signal features and/or change points have been identified, they can then serve as labels for the supervised learning models described in the previous section. These models can then be trained to learn precursors and predict the identified change points and features which correlate to the physiological events of interest.

The methodology decision will be made at the approximate half way point of Phase One, and will be primarily driven by the availability of data sets annotated with the PE of interest, as well as finding in the published literature. In addition to the methodology decision, Phase One will also include the full development of the single person alert system. This include the UI development and usability study of said system and UI. There are multiple operationally relevant research questions to be answered in Phase One that will determine the direction of Phase Two. At the conclusion of Phase One, we will have determined the best way to train the device to each warfighter's normal, selected which device we plan to move forward with, and determined the best process for the device to communicate with the platform, and developed the first generation alert system in accordance with MIL-STD-1472-G.

Phase Two is expected to take approximately 12 months. Phase Two will consist of three major initiatives that will take place in parallel. The largest initiative will be to incorporate multiple devices into the Phase One system and create an intuitive user interface (UI). The goal during Phase Two would be to track teams of up-to-ten Warfighters from a single remote monitor. The second initiative is to further develop algorithms for detecting other PEs. Since the PEs addressed in Phase One, such as hyperventilation and anxiety, are classified as easier to detect, the remaining PEs addressed in Phase Two may prove more difficult to detect and may take longer to train an algorithm. The team intends to deliver a system capable of detecting all required PEs per the sponsor's direction. The third initiative is to develop a readiness score for each individual so the team lead can see which members are either dealing with an injury or at a higher risk of injury due to overexertion and fatigue. The readiness score is intended to be the most useful for real-time decision making and mission planning.

Throughout the development process of the application and UI, the team will conduct usability testing to ensure the UI and form factor most adequately support the systems goal of detecting and preventing Warfighter injury. This will be a significant effort to ensure the system is designed in such a way to optimize usability while decreasing error. The system will be tested for quality and usability in a

current ONR-funded set of test events such as Kobol. Kobol allows government and contractor researchers to develop new technologies for augmenting the Warfighter and test these technologies in a force-on-force combat situation. Kobol is largely centered on the development of autonomous ground combat systems wherein a large group of the traditional squad layout will fight against a smaller team augmented by these autonomous systems. This provides a Limited Objective Exercise for human performance researchers to be able to use Wearable technology to evaluate the performance, health status, stress, and workload of individuals on either side of the technology paradigm applied to combat.

The proposed system will include Commercial Off-The-Shelf (COTS) wearable devices and an Android-based application with a custom interactive UI. The application would be loaded onto the existing, portable command and control devices already in use by each team leader and corpsman/medic in theater. The data can ultimately be integrated into after action review software tools such as those currently being developed by ONR led by Dr. Peter Squire (ONR Code 341). Using the UI, the team leader and corpsman/medic will have objective information to build a better picture of the situation, more quickly address all injuries, adjust mission tactics based on individual and team physiological state, and provide feedback for how to optimize team and individual performance. UI will include information such as, but not limited to, time spent running, engaging with enemy, risk of PE, workload, stress, HR, HRV, and temperature, to help quantitatively inform decision making as well as provide performance feedback of past mission. Effort will include delivery of the prototype system as well as description of methodology to evaluate the system and its efficacy. Methodology and results will be delivered in a white paper. This program will integrate the state-of-the-art technology with the Warfighter to increase awareness of individual and team physical states for decision making and planning. Ultimately, the information provided will become part of the command and control (C2) and force protection (FP) calculus for maximizing Warfighter performance and minimizing unnecessary injuries.

Collaborators

The primary team consists of biomedical, systems, and human factors engineers, AI/ML experts, psychologists, software developers, naval operation experts, and human performance researchers. Although the majority of the work will be performed in-house, the team has some collaborators that will be involved. The team will work closely with the Expeditionary Medicine team at NSWCDD, who have vast experience aligning technology solution with the mission needs and requirements expressed by the Fleet Marine Forces (FMF) Naval Health Services Support (HSS) community (headed by The Medical Officer (TMO) of the Marine Corps) and the medical acquisition sector, specifically MCSC, PM-SMS. Their involvement will allow for collaboration with the medical community as the system is designed to meet the Warfighter's need. These SMEs provide valuable insight into the medical operations of the military and the currently gaps. Another one of the collaborators will be Dr. Rachael Markwald from Naval Health Research Center (NHRC). Her team are leaders in Warfighter fatigue research and have supported previous efforts in developing fatigue inducing test protocols. Although fatigue detection is not specifically called out, understanding and addressing fatigue will be vital to predicting injury risk and providing an all-encompassing system. NWSC Dahlgren also has leaders in the chemical, biological, and radiological field (chem-bio). The Human Performance and Augmented Warfighter team has worked closely with the chem-bio group and will utilize their expertise to investigate the integration of a chem-bio sensor into the wearable device. Detecting agents in the air is more effective than detecting physiological symptoms in response to a chem-bio agent because it can provide the Warfighter with an

alert to vacate a contaminated area before any physiological damage is done. Although chem-bio detection is not in the initial design to save costs, the group will be involved throughout the project as chem-bio sensors will likely be added in future iterations and transitioned to the fleet. Additionally, the team will work with the Human System Integration branch at Dahlgren to test the alert system on the USS Monterrey, a naval ship used for testing and validation of new technology, for further operational evaluation.

Future Opportunities

Upon successful demonstration of prototype system, product can be enhanced to include GPS tracking when PE is detected. This will allow team leaders to quickly locate and provide medical support to the injured Warfighter. Lower body injuries are common even for healthy Warfighters when their bodies are not showing signs of risk. Integrating electromyography (EMG) sensors and gait analysis software could identify when a Warfighter has an injury but has not reported it or is at high risk for injury. The team has had recent success with body pose estimation algorithms to detect and classify an individual's risk of injury due to poor posture. Similar techniques can be applied by using the device's accelerometer to detect changes indicative of injury or risk of injury. The data could be used for customized training based on the individual's physiological readiness for activity. Physiological measures could also be useful in identifying stressful situations such as enemy engagements without the need for communications. Often the Warfighter will have a "gut feeling" that something is about to happen, but it is not verbally communicated due to the lack of information. However, the physiological measures due to increased stress may be picked up from the Warfighter's body and automatically sent to the Command Operations Center or the remaining squad members. This information could be used to quickly adapt the execution of the mission if a certain unit was overly fatigued, injured, stressed, etc. Wearable technology is a new field and the technology is continuously advancing and becoming more commercially available. In order to make best use of these technologies, we must first explore and gain an understanding of the systems in combat environments. Once validated and opportunities are understood, these technologies can be integrated with the Warfighter to paint a better picture of the battlefield and ultimately create a safer and more effective Warfighter.

Overview

Phase - Task	Description	Schedule (Notional)	Impact if Not Funded
Phase 1- Task 1 *Select equipment and data sets*	Evaluate and compare COTS wearable devices, procure and test the most promising devices, identify and access relevant medical data sets. Literature review for PE signal features.	Months 1-3	Failure to compare devices could result in the procurement of incompatible devices. Without searching for available data sets and neglecting extensive literature review, we may develop a solution more complex/expensive than required.
Phase 1 – Task 2 *Train ML algorithm*	If data sets are available, train algorithm to detect selected subset of PEs (anticipation to address loss of consciousness, hypoxia, and seizure first). If data set is not available, pursue option 3 or 4 above and build/label data set.	Months 3-12	This step will not be needed if enough labelled data set can be found; however, it is unlikely that there will be sufficient data and we will need to train and ML model. Without training the model, the system will not be able to accurate detect PEs.
Phase 1 – Task 3 *Develop System and UI with rudimentary detection abilities*	Build system around selected wearable device to detect 3 selected PEs. Develop UI to easily view data. Iterative process involving software, biomedical, and human factors engineers.	Months 3-15	Without building the system, the wearable device will not be able to alert when PE is detected.
Phase 1 – Task 4 *Usability study and UI update*	Develop usability test procedures to analyze initial system. Coordinate with active duty Warfighters (end users) for operational usage and feedback. Adjust the UI based on the results from the study.	Month 13-15	Without development of future concepts for testing and validation, prioritization of certain system development will be based on requirements established, without validation and lessons learned will not be known until late in development cycle. Conducting autonomy concepts development during early stages will reduce the number of options required for consideration in later design stages.
Phase 1 – Task 5 *Finalize and present Phase 1 success to sponsor*	Document and present current state of system. System should be able to detect 3 different PE with high accuracy. Results will be presented to sponsor.	Month 16	Without documenting and present to sponsor, the team will not be able to address sponsor concerns or respond to change in direction/schedule.
Phase 2 – Task 1 *Incorporate multiple users in single system*	Update system to include 5 person team alert system. UI will display all 5 members and their near-real-time health status. Human factors will be included throughout design.	Month 16-22	Without sensor integrating multiple users, the team lead monitoring and tracking individual alerts will have to have a different tablet for each team member. This is highly inefficient and would not be accepted by the end user.

Phase - Task	Description	Schedule (Notional)	Impact if Not Funded
Phase 2 – Task 2 *Enhance detection algorithm*	Enhance system to detect rest of desired PEs based on literature review and sponsor discussions.	Month 16-25	Without training an algorithm on all desired PEs, the alert system will not detect if Warfighter is experience one of the PEs that the system has not learned. System would be incomplete and risky to field.
Phase 2 – Task 3 *Create and include fatigue profile in system*	Use physiological measures to develop individual fatigue profile. The profile will populate the team lead's table for understanding of each team member's physical readiness and risk of injury.	Month 21-28	Without a fatigue profile, the system will not detect and aid in the prediction of fatigue-induced injuries. Most common injuries stem from muscular and cardiovascular fatigue, so a fatigue profile is vital in preventing such injuries.
Phase 2 – Task 4 *Usability Testing*	Develop usability testing for whole system. Test will include multiple participants performing extended periods of physical exercise. Operational personnel will collaborate and provide feedback regarding field usability. System will be adapted based on test results and feedback.	Month 27-29	Without performing usability testing and consulting operational SMEs, the system may not be optimized for use in the field.
Phase 2 - Task 5 *Deliver system*	System will be delivered to sponsor including all documentation and reports. Final demonstration to stakeholders and transition sponsors.	Month 30	Without documentation, it may prove difficult to operate and or troubleshoot system. Without demonstration and marketing to stakeholders may lead to technology "being put on the shelf".

Funding Requirements

Funding Breakdown	Funds Required Year 1	Funds Required Year 2	Funds Required Year 3 (6 month)
Labor	$578,125	$890,650	$375,000
Travel	$10,000	$25,000	$10,000
Equipment (Direct Cite)	$50,500	$37,500	$0
Funding Required:	**$638,625**	**$984,375**	**$385,000**

Total Funding Requested: $2,008,000