Designing a Smart Helmet for Wildland Firefighters to Avoid Dehydration by Monitoring Bio-signals

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ABSTRACT

Smart Helmet is a new wearable device to monitor wildland firefighters' real-time bio-signal data and alert potential health issues, i.e., dehydration. In this paper, we applied the human-centered design method to develop Smart Helmet for firefighters. We initially conducted multiple rounds of primary research to collect user needs and the deployment constraints by interviewing 80 firefighters. Targeted on dehydration caused by heat exhaustion and overexertion, we developed a smart helmet prototype, named FireWorks, with an array of sensors collecting the firefighter's bio-signals, including body temperature, heart rate, and motions. When abnormal bio-signal levels are detected, the alert system will notify the firefighter and their supervisor. The notification is achieved by an on-device algorithm that predicts imminent health risks. Further, we designed a mobile application to display real-time and historical bio-signal data as well as alert users about potential dehydration issues. In the end, we ran user evaluation studies and iterated the prototype based on user feedback, and we ran the functional evaluation to make sure all the implemented functions work properly.

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CCS CONCEPTS

• **Human-centered computing → Interaction devices**; • **Hardware** → *Wireless devices.*

KEYWORDS

Firefighting, wearable, bio-signal, health sensing, sensor, dehydration

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1 INTRODUCTION

Dehydration is a frequent problem for wildland firefighters during their deployment in the field. A series of heat-related illnesses such as heat cramps, heat exhaustion, and heatstroke [15] affect the health and wellness of wildland firefighters. This paper describes how we designed a smart helmet to include a sensor array, an alert system, and a corresponding mobile app to distinguish different scenarios in the field. We also describe how we run different rounds of user evaluation and what functions we add to improve the user experience. User experience is the core of our design, whether we are developing the helmet, implementing the App, or building the original algorithm. We want to use this paper to demonstrate how we build this human-centered smart helmet to protect the wildland firefighters and improve the user experience. Finally, we described the functional testing progress and feedback at the end of the paper to demonstrate that all of the implemented functions work and all of the algorithm's events can be triggered.

2 BACKGROUND AND RELATED WORK

2.1 Wildland Firefighter Deploying

Wildland firefighters working in extreme conditions with consecutive shifts face multiple stressors, such as woodsmoke exposure [1, 3], heat[2, 13], sleep disruption[2, 7] and so on. These stressors could lead to lifelong asthma [1], impact their cognitive performance and sometimes [2], even cause death. Since 2000, 313 wildland firefighters have lost their lives on the field [5], and 54% of them were caused by overexertion under hot and challenging conditions [20]. Wildland firefighting typically requires longer (12–16+ hour days) and arduous work shifts (4,000–6,000 calories expended a day) for up to 14 continuous days [4], which would increase the risk of getting heat overexertion. A crew supervisor's primary responsibility is to lead their crew in the safe and effective completion of assigned work [16]. They need to work on the field alongside their assigned group of wildland firefighters during deployment. The current method to detect heat exhaustion and overexertion incidents is by human observation, which can be too slow and inaccurate in assessing different heat-related conditions. As researchers suggest that early management of dangerous situations and timely rest can help firefighters work safely and efficiently[7, 13, 19], we proposed a set of health monitor and feedback systems to help both firefighters and supervisors manage their health condition.

2.2 Relevant health monitor devices

Kremens, Faulring and Phillips [12] developed a portable device that can monitor the external environment (temperature, carbon monoxide concentration, GPS location) and internal state (body temperature, heart rate and movement) of the firefighter, and they use LED lamps and sound as alerting signals. This device needs an external antenna for data transmitting, and the main part of the device is put in the pocket or somewhere else while the alert and switch part should be put on the shoulder of firefighters. However, they did not indicate where they put the sensors and how they deal with the data. ProeTEX [17], an European Integrated Project aims to monitor multiple biosignals of rescuers, such as ECG, internal and external temperature, heat flux and even respiratory rhythms. The members of the project work on each parameter separately and most of their form factors are jacket or T-shirt. As firefighters already take many equipment while deploying, some researchers [8] think we should enhance the existing pieces that firefighters can easily bring and maintain. Hence, Helon [8] and Jeong et al. [10] both came with the idea of equipping a firefighter's helmet with cameras for environmental assessment.

3 METHOD AND RESULTS

We researched the placement of wearable devices and the alert system to find the solutions that can work under a variety of deployment environments and understand the user needs. We used the findings to analyze various iterations of prototypes, and the user evaluation results helped us generate the final solution.

3.1 Wearable Device Research Method and Results

We interviewed 15 crew supervisors and surveyed 80 wildland firefighters to understand their needs, the environmental work conditions, and design requirements to use in the development of a technology solution that wildland firefighters and their crew supervisors would adopt and use. Eight questions for the interview and 12 questions for the survey were developed. The interview and survey can be roughly divided into three sections: (1) Deployment Environment, (2) Wearable Device, and (3) Communication Flow.

The **questions** included: (1) What equipment and devices do wildland firefighters need to bring to the field? (2) What kind of wearable devices and location for placement on their bodies are more acceptable for use during the deployment? and (3) How do wildland firefighters communicate with each other in the field?

The **results** included: (1) Each wildland firefighter needs to carry over 60 lbs in weight during their deployment, (2) Sometimes there is no Wi-Fi or cellular connection in the field. They have to use a separate wireless communications platform called FirstNet by AT&T to get wireless service. (3) Radio is their primary method to communicate with each other, but sometimes radio loses messages, and (4) Watches and helmets are the two most practical form factors for wearable devices in the field.

The findings from our surveys influenced the design decision to develop a Smart Helmet wearable device since 70% of the wildland firefighters are not in the habit of wearing a watch in the field, but all of them must wear a helmet during their deployment in the field. Bluetooth Low Energy (BLE) was selected as the communication protocol to transmit data between the helmet and the app since it does not require large amounts of data and can run on battery power for a long time at a low cost [18].

3.2 Alert System Research Method and Results

To research the appropriate method to implement the alert system, we conducted medical expert interviews with three medical experts. One of the medical experts is researching using skin temperature and heart rate to estimate physiological strain during exercise in the heat, which is similar to our project. We prepared 8-10 interview questions in three sections: (1) Health Data Changes, (2) Physiological Strain Index, and (3) Sensors. During each interview, one team member led the interview, and another team member took notes and recorded the interview.

The **questions** included: (1) How will the heart rate and skin temperature on the forehead change when heat-related illness becomes severe? and (2) How can we use the Physiological Strain Index to estimate people's health status?

The **interview results** included: (1) The forehead skin temperature will keep increasing when heat-related illness becomes more severe. The skin temperature will rise slower when people experience heat exhaustion due to an increase in sweat on the forehead, (2) The Physiological Strain Index is more suited for measuring skin temperature and not core temperature, and (3) Monitoring heart rate on the head is challenging, but industry-level heart rate sensors can be used to collect smoother data compared to hobbyist heart rate sensors in our earlier prototypes.

Our research identified that we could not use the Physiological Strain Index in our algorithm since some factors do not match our project [11, 14]. We decided to use forehead skin temperature and heart rate to distinguish different heat-related illnesses and trigger the alert system.

Based on the results from surveys and interviews, we refined our problem statement to the following: "How might we leverage technology to monitor wildland firefighters' physical condition so that potentially hazardous situations can be anticipated?"

4 SOLUTION

Our Smart Helmet prototype aggregates heart rate, temperature, and movement data to alert firefighters and their supervisors about potentially hazardous situations, such as: heat exhaustion, heat-stroke, and dehydration. We designed a Smart Helmet with sensors to collect data, an alert system to notify the firefighter, and a corresponding mobile app for visualizing the data for the crew supervisor. The firefighter's helmet transmits data to the mobile app over BLE, and the mobile app transmits data to the cloud database (Figure 1).

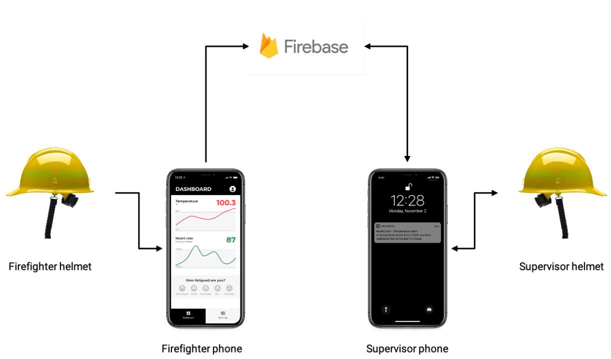

Figure 1: Overall solution. The mobile app for the supervisor captures data from the cloud database and sends the alert to the Smart Helmet when abnormal data is detected.

4.1 Smart Helmet for Data Collection

We used the Feather nRF52840 as the processor since it is cheaper than the Arduino Uno, and it also has less power consumption than other processors [9, 21]. The Feather nRF52840 also contains Bluetooth Low Energy (BLE), which can run on battery power at a lower cost than Bluetooth [18]. We connected the heart rate sensor (POLAR OH1+), the infrared temperature sensor (GY-906 MLX90614ESF), and the accelerometer (Adafruit LIS3DH) to the Feather board to collect the firefighter's real-time health data. The sensors and board were placed on the corresponding locations of the helmet to receive consistent data (Figure 2). Based on the sensor testing, we found that heart rate is difficult to collect when the sensors are on the head. Therefore, we used the industry-level heart rate sensor, which connects with the processor by BLE, to collect the heart rate data. There is also an SD card on each helmet as the backup database to store the data, in addition to the cloud database which stores the data at the same time. The app acquired data from the cloud and visualized the data to the users.

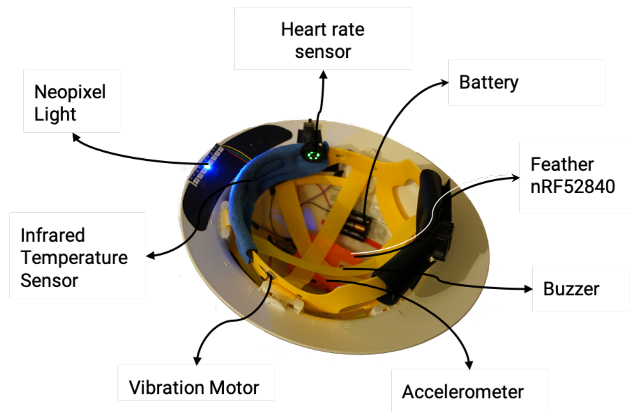

Figure 2: FireWorks Smart Helmet. We connected one industry-level heart rate sensor, one infrared temperature sensor, and one accelerometer with the Feather board to collect health data. Then we connected one NeoPixel light, two vibration motors, and one buzzer with the Feather board as the alert system to notify the user.

4.2 Alert System

When firefighters experience heat-related illnesses, the body temperature and heart rate will exceed the normal range. We used these data plus the movement data to build the algorithm for the alert system [6, 22]. Based on the wildland firefighters' interviews, we increased the threshold since our target users have a higher heat tolerance and stronger body than regular people. We also wanted to avoid too many false positive alerts.

We connected NeoPixel lights, two vibration motors, and one buzzer with the Feather nF52840 on the Helmet on the hardware side (Figure 2), and we developed an algorithm which contains nine events (Table 1) that can distinguish different heat-related illnesses and predict possible incidents on the field. We divided these nine events into four categories, and we used various combinations of alert signals to represent each category.

The four categories are (Table 1): (1) **Helmet off:** The NeoPixel light turns on in mode LOW, and buzzer turns on, alerting that the user has taken his or her Helmet off during deployment (2) **Firefighter Fall down:** The NeoPixel light turns on in mode HIGH, and the buzzer turns on, alerting that the user has fallen down on the ground, (3) **Drink Water:** The NeoPixel light turns on in mode HIGH, and vibration motors turn on, reminding the user to drink some water and take a break, and (4) **Severe Situation:** The NeoPixel light turns on in mode HIGH, and vibration motors and buzzer turn on simultaneously, alerting that the user is experiencing a severe situation such as heat stroke, heat exhaustion, and high heart rate.

The supervisor receives alerts on their phone when the firefighter is experiencing Helmet off, Firefighter Fall down, or Severe Heat-Related Illnesses.

Table 1: Algorithm Events and Categories. HR represents Heart Rate. Acc represents the square root of the sum of the x square, y square, and z square of the accelerometer. Temperature Delta represents the initial temperature minus the current temperature.

Number	Event	Category
1	Temperature Delta is smaller than -15 degree F for 10 seconds. (set buffer)	Helmet off.
2	Acc is greater than 20 and one of x or y is greater than 7 for 20 seconds	Firefighter Fall down.
3	HR beyond vigorous range (> 90%) over 3 minutes	Severe Situation
4	HR beyond vigorous range (> 90%) for 60 seconds.	Drink Water
5	The Temperature Delta is greater than 7 degree F over 1 minute	Severe Situation
6	The Temperature Delta is in the greater than 3.5 degree F for three minutes	Severe Situation
7	The Temperature Delta is greater than 3 degree F over 1 minute	Drink Water
8	HR is in vigorous range (75%-90%) for over ten minutes	Drink Water
9	Every 15 minutes if none of the statements above are TRUE	Drink Water

4.3 FireWorks App for Data Visualization

Once the Smart Helmet collects health data and the algorithm's events are triggered, the Smart Helmet stores the data in the local database and send them to firefighter's phone. Then the data will be sent to our cloud database and transmitted to the supervisor's phone. The wildland firefighters can use the app to check on their current health status and update their current status to their supervisors. The supervisors can use the app to check the firefighters' health data and get alerts when the health data are abnormal. (Figure 3) To help the wildland firefighters and supervisors understand the data, we used red color to label the abnormal data and fill the abnormal range in the graph.

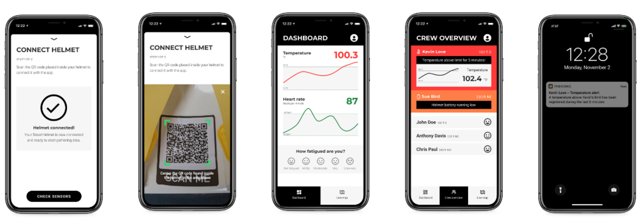

Figure 3: Screens of the FireWorks App. (From left to right) The first two screens are how the users connect to their helmets. The third screen is for the wildland firefighters, and the fourth together with the fifth screen are for the crew supervisors.

5 USER EVALUATION

After prototyping the Smart Helmet, alert system, and the corresponding app, we invited wildland firefighters and crew supervisors from local fire-fighting departments to evaluate the prototype. Following the local recent user study policy due to the Covid-19, we did the remote user evaluation instead of the in-person user evaluation. We asked eight participants to watch a demonstration video about different combinations of the alert signals and asked them to evaluate the pros and cons. We then invited them to follow the task list and use the wireframe version of our app. We asked them to rate from 1 to 5 (5 being the highest), for whether a function is straightforward and easy to control.

Qualitative conclusions from **wildland firefighters** included: (1) Firefighters need clear instructions to use the Smart Helmet, and they might get confused on when to put on the helmet, (2) It is hard for firefighters to understand their health status by only using the raw data during deployment, and (3) Having alerts periodically to remind them to rest and hydrate will cause users to disregard them or find a way to diminish them.

Qualitative Conclusion from **Crew Supervisors** included: (1) There was some confusion once the supervisors received the phone alert about their firefighters. The supervisors do not know what to do next, and (2) When the supervisors use QR codes to add a new crew, they do not know how to jump into the next step.

Prototype revisions based on the results: (1) We highlighted the notice with a clear introduction for each step, (2) We used red color to fill the dangerous range in the graphs and use red color to label the abnormal data, (3) We added a WARNING sign at the beginning to emphasize the severity and added a notice at the end to encourage them to click the alert first, and (4) Edit the design, let the scanning box disappear, and automatically jump to the next step after scanning the QR code.

6 DESIGN CONSIDERATION

Throughout our research and prototype iterations, we have made some design considerations based on data and feedback from our subject matter experts.

6.1 Smart Helmet Device

User experience played a big part in our design considerations. From our user research through expert interviews, field study and surveys, we learned about our users' current workflow, working conditions and pain points. After consolidating our findings, we were able to come up with the most suitable form factor for our device and we decided to develop a Smart Helmet because it would be the least or not at all intrusive to their job as wildland firefighters are required to wear their helmets at all times during deployment in the field. For example, chest and wrist straps can give better heart rate readings but it may interfere with operations on the field based on feedback from our survey and also firefighter interviews. The next design consideration we had to decide is the form and placement of the sensors. With the device having to be integrated around the helmet area, we explored several sensors and placements. For example, the heart rate sensor, we tested it on the earlobe, in front of the ear and also on the side of the forehead and got feedback from our potential users that they would prefer a wearable that does not protrude far from the helmet because it would be less robust and might snap off easily due to their working conditions.

For our battery choice, we were initially using Lithium Polymer (LiPo) batteries to power our system, however, there were concerns about our user's safety since this device is located on someone's head. Wildland Firefighter's helmets are subject to impact and that might cause the cells of the LiPo battery pack to get punctured and that could potentially cause a violent chemical reaction when exposed to the air and might lead to an "explosion". Therefore, we decided to go with alkaline batteries to power our system, as they do not pose a risk of explosion. Although we use blue LED light for our alert system to stand out in our user's environment, we also were aware that some firefighters might be colorblind. Therefore, we want to be inclusive and give the users an option with colorblind-friendly colors with our RGB LEDs embedded in the helmet. With wildland firefighters working in a possibly fast paced environment, we included a QR code for them to easily connect their mobile phone to the helmet without having to scroll through multiple helmets nearby or by entering a code.

6.2 Mobile App

For a new user, we want to make sure the creation of an account and connecting to a helmet is as seamless as possible. When creating profiles, there are usually concerns from users when they have to input personal information and how this information will be used. We went through several UI/UX iterations and at the end made sure that we removed inputs for unnecessary user information. For our algorithm to work, we require our user's age to predict the possible hazardous situations. However, the exact day and month doesn't really matter as much. Therefore, for our final prototype iteration, we removed those inputs and only required them to input their birth year. The same goes for the user's gender, some users might not be comfortable stating it, therefore for our final iteration, we removed that input but still managed to get our algorithm working without it. For users to be able to check their current health status, we added a real time graph with the moving average of their heart rate and body temperature. From our user evaluations, we found that users were not able to tell when their health is in danger, we later added more colors for visualizing hazardous situations. For example, red color is now used for the graph to show that the user is in a dangerous range. In our app user flow, we also added notifications to pop up when they completed a step during the on-boarding process so they know they completed a step.

7 DISCUSSION AND FUTURE WORK

Based on the previous user evaluation feedback, we added more functions in the FireWorks App, and we implemented all of the functions as we planned before. To improve the user experience, we added clear instructions on each page to teach the user how to create a profile and connect the App to the helmet. From the user evaluation, we learned that most users have trouble reading the data, and they also do not know the current standard level for each health metric. To help them better understand different situations, we updated the data visualization method and used a graph with different colors to show the data changes. Based on the final functional evaluation, all of the implemented functions work properly, and we have updated all of the functions based on the user evaluation feedback to optimize the user experience.

We added an SD card on the helmet, and we created a cloud database. We planned to use the cloud database to realize the data transmission among devices, and we used the SD database as back-up storage for the data. From the functional testing, we compared the data in the SD database and the cloud database, and we found out that two curves overlapped with each other, which means both of the databases are stable and can work properly.

The WiFi and Cellular connections are poor in the field, and the users had a hard time to send information to others by using tools other than the radio. We used Bluetooth Low Energy to transmit data between the helmet and the App to solve this problem. The helmet can work consistently for over three hours, with only half-second data lost. We want to use stability to improve the users' experience and attract more users, and stability is one of our product's advantages for competitiveness and adoption by wildland firefighters.

Our product contains the original algorithm. This algorithm is the core tool to distinguish different heat-related illnesses, and this algorithm is also our key to compete with other competitors. There are nine events in the algorithm (table 1), and all of them can be triggered successfully from the function testing. We divided these nine events into four categories based on severity, and each category corresponds to one type of alert. We interviewed several medical experts, and they authorize the algorithm. Since our ultimate goal is to design a human-centered smart helmet that can satisfy the user's needs and maximize the user experience, we have to consider that wildland firefighters have higher heat tolerance, which might cause negative alerts. Therefore we increased the threshold in each event to avoid negative alerts.

In the future, improving the user experience is still our main goal. We want to implement more functions, such as the location information and supervisor notification, to keep tracking their firefighters and get notified about different dangerous incidents quicker. Even though we are using BLE to transmit data between the helmets and the App, we still require WiFi or Cellular to transmit data between the cloud database and the App. Also, we plan to update the communication channel and create a reliable peer to peer communication that can be used in the absence of cellular data. Then, we want to run more user evaluations after COVID-19 to test the functions and make the product more user-friendly. Finally, we plan to customize our design and build a smart attachable standalone device that can fit all helmets. In this case, we can reduce the cost and realize mass production.

8 CONCLUSION

The FireWorks Smart Helmet is a human-centered product that can distinguish different heat-related illnesses by using the forehead skin temperature, movement data, and heart rate. We researched and developed an alert system and a corresponding App to work with FireWorks Smart Helmet such that the wildland firefighters and crew supervisors can be immediately notified when the Helmet detects abnormal health data. We have made different versions of prototypes and update lots of functions based on the primary research and user evaluation to optimize the users' experience. Overall, we have shown that the Smart Helmet has the potential to save more time for the users to diagnose heat-related illnesses in the field and improve the overall health of the wildland firefighters in the field. Crew supervisors evaluated the Smart Helmet and determined that it could assist them in monitoring the health of wildland firefighters and save lives. We are further developing this product in the context of user experience for both the crew supervisors and the wildland firefighters.

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