Supporting Safer Work Practice Through the Use of Wearable Technology

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ABSTRACT

Forestry has the highest accident rate of any industry in New Zealand. One of the known contributors to accidents is worker fatigue, which can be attributed to the long working days and physically (and/or mentally) demanding nature of the work. Wearable technology is increasingly being proposed within work environments as a way of supporting workers in different tasks and monitoring workers in hazardous environments. However, in most cases 'off the shelf' wearables are not fit for purpose in rugged outdoor environments. Over the past five years, we have conducted numerous studies and undertaken research into the use of wearable technology in New Zealand forestry. The work aims to address existing problems by developing ethical and evidence-based wearable technology which is suitable for forestry workers. We describe the development of a smart vest for forestry workers along with key insights gleaned from the development, design and testing processes.

KEYWORDS

Wearable technology, occupational health, data ownership

Introduction

If the future of work and worker safety involves wearable technology, how do we ensure it is fit for purpose? By fit for purpose we mean that it is usable in the intended environment and that it acceptable to the workers, e.g., is ethical. In this paper we describe the human factors challenges that arise when developing wearable technology for workers.

The forestry industry in New Zealand has one of the highest number of fatalities and serious injuries in the country with a fatality rate of 56.73 per 100,000 workers in 2018. Forestry workers are six times more likely to be seriously injured and 22 times more likely to be fatally injured than in other NZ industries (Ministry for Primary Industries, 2019). While the specific forestry setting is unique, other outdoor-based and labour-intensive industries, such as mining, haulage, all-terrain farming and fishing, encounter similarly hazardous situations.

While there are various factors that contribute to accidents, worker fatigue has been identified as a major contributor (Safetree, 2016). Our research aims to predict potential health hazards in outdoor work situations by using lightweight, wearable technology, relying on correlations between mental and physical fatigue (Hockey and Ebrary, 2013) and hazardous situations. Forestry work involves manual labour in combination with heavy machinery. As most forestry workplaces are situated in remote locations, the worker crews have to travel before dawn to their workplaces. Travel may take more than two hours each way and work often involves long hours in remote settings without shelter. Hazardous situations arise during harvesting (using a mix of chain saws and heavy machinery), breaking out (removing felled trees), quality control (marking up logs prior to removal) trucking and silviculture (manual planting of small trees). Driving to and from worksites (partly on unsealed roads) also includes road accident hazards.

Figure 1 shows the components that make up the architecture of our proposed solution. The workers have wearable monitoring devices (green boxes) and outputs (red boxes) and these are connected to both onsite and cloud processing. In order to develop such a wearable technology infrastructure, we need to consider the physical nature of forestry work and the different roles workers undertake. We also need to consider the lack of communication infrastructure that exists (beyond two-way radios) and the fact that the rugged nature of the terrain and the movement between different parts of the forest as clearing occurs means that no permanent set up is possible.

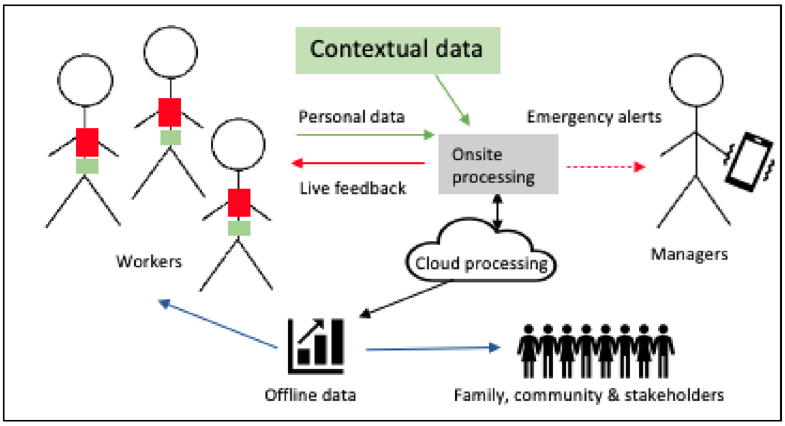

Figure 1: Components of the wearable architecture

Related Work

Wearable technology and smart clothing has been popular in the military for many years. It is typically used in these environments to monitor health and location of military personnel (Hoyt et al., 2010) or embedded with robotics to advance human capabilities, for example the Darpa Warrior Web project (Darpa, 2014). As the technology has become more commonplace, it has been promoted as a way of supporting workers in high risk environments. For example, monitoring worker exposure to gases in mining (Hazarika, 2016), tracking workers for safety in offshore oil and gas rigs (Sinha and Vyas, 2018).

More recently the popularity of fitness trackers and smart watches has given rise to a new type of worker tracking. Firstly, there are companies who seek to promote the health of their workers by encouraging them to be active and provide trackers for personal employee use to support this. For example, Target in the U.S. have offered to give FitBit trackers to all of their workers to increase awareness about healthier lifestyles (D'innocenzio, 2015). In a similar manner, although with more focus on rewarding adherence, oil company BP tracks step counts of workers and offer lower health care premiums to those who meet certain criteria (Young, 2015). According to technology research company Gartner, about 2,000 companies offered their employees fitness trackers in 2013. In 2014 this rose to around 10,000, and companies such as FitBit now have dedicated partnerships with organisations to provide large numbers of trackers and personalised data provision. The collection of such personal data and its use raises many ethical questions about how such data is used and who has access to the information - for example what happens to the employee who does not meet the fitness criteria defined by their employer? We discuss this later in the paper as it pertains to our case study and our opinions as researchers collecting such data, as well as employee reactions and 'buy in' to such initiatives.

Previous evaluations have been conducted on a wide range of wearable technologies including both consumer activity trackers as well as specialist devices designed for outdoor work environments.

Typical findings are that not only do these not provide accurate and reliable data, they also restrict access to the raw data captured (Bowen et al., 2015; Bowen et al., 2017). Early concepts that had been proposed for similar outdoor work environments, such as a vest for construction workers in Australia that could check for heat-stroke were never explored under real-world working conditions (Edirisinghe and Blismas, 2015). Devices which predominantly focus on athletes or specific heath care situations, were found to be too costly for use in forestry and were not customisable for different work contexts. This led to the development of our own wearable data capture tools and in this paper we discuss the design requirements, development and testing we have undertaken for a smart vest. The smart vest collects real-time data (heart-rate, heart-rate variability (HR/HRV), galvanic skin response (GSR), motion) from forestry workers. While our project has a wider focus than just the wearable technology for the workers (see Figure 1) in this paper we focus only on this aspect.

Design process and experimentation

Early experimentation into fatigue identification by wearable technology demonstrated to us that we needed to prioritise the following two aspects:

1. Data to be collected must be meaningful and measurable
2. Personal data that is collected from individuals must respect their data ownership

For data to be meaningful, we must be able to use it to accurately infer fatigue, or risk of fatigue. This means that we cannot use single data items without surrounding contextual data. For example, if a manual feller has a heart rate that rises to 165bpm we also need to consider what he is doing and how long his heart rate remains raised. If he is actively felling trees and his heart rate begins to drop once he stops then this will contribute to overall fatigue but is not an immediate cause for concern. If, however, the rise occurs during a rest break then it may indicate a medical emergency. For data to be measurable we need to be able to accurately capture it (within acceptable margins) within the work environment. This requires that we design any wearable equipment for the specific forestry work environment, i.e. for physically demanding roles in a rugged outdoor environment. This relates to the wearability for the workers, the size and positioning of sensors and hardware must be such so that it does not cause any discomfort and does not lead to additional hazards (e.g. external straps that may catch on tree branches or equipment). It also relates to the environment of use, battery life, network capabilities, the ability to remove hardware so that clothing can be washed etc.

Our intention is that the ownership of any personal data collected from the workers remains with the workers themselves and that all wearable solutions that are developed are ethical (i.e. are used to support worker safety than provide management tools). This also means that any new data that is generated, by analysis for example, also belongs to the workers. In addition, the types of data that is gathered and who has access to any results must be acceptable to the workers. We had already removed the use of sleep tracking as being too invasive and unlikely to be adhered to by the workers. Previous studies in the forestry industry with a commercial sleep and fatigue management system had demonstrated that this was the case (Griffiths et al., 2017). There is the potential that data gathered from workers (particularly with respect to fatigue and being ‘fit for work’) can be used as a management tool and lead to workers being sent home without pay or even laid off. This reinforces the need to ensure that data is used only for specific purposes within the workplace. Primarily this means providing notifications to the workers themselves or pairing workers together. Notifications are only sent to supervisors and managers in case of extreme hazards or emergency. Similarly overviews of data are provided to the workers outside of work and they can opt to share this information with family members, they can also control the level of detail made available to central reporting systems (which may be used by the forestry management companies for reporting).

Determining Requirements

Requirements for the design of the shirt were developed with the environment and tasks that the forestry workers have to undertake in mind. The primary requirements are that the shirt is:

1. Non-Intrusive – should not interrupt the forestry workers work activities
2. Comfortable – must be wearable all day as part of work clothing
3. Lightweight – the added weight of the electronics and sensors must be minimal so as not to affect comfort
4. Compact – electronics and sensors cannot be bulky or protruding
5. Durable – must be suitable for use in various harsh conditions, from heat to cold, wind and rain and rubbing and catching on scrub and trees as they are felled and processed
6. Cheap – large numbers of workers will need to be monitored in an environment in which equipment can be easily damaged or lost
7. Washable – the shirt will need to be able to be washed, therefore all electronic components must be easily removable

These requirements were used to determine the material and shape for the vest as well as the positioning of sensors and electronics. The electronics for the vest consist of three sensors (ECG-style heart rate sensors, galvanic skin response sensors and an accelerometer). These are connected to a small processing unit that is integrated into the shirt (but easily removable), which performs initial data analysis and calculations before uploading data to the base station (see Figure 1).

Heart-rate sensors can be located in several different positions on the body. Whilst the ears and forehead are both good locations due to the high blood perfusion rate in these places, the connections between all sensors and the on-board processing unit means that it is desirable to have all sensors placed as close together as possible. Several periods of experimentation were undertaken where sensors were located in various positions on the body and compared against baseline measurements (e.g. using a wrist worn heart-rate monitor and finger sleeves for GSR measures). Once satisfactory locations had been determined we then had to similarly consider where on the body the processing unit should be located. Further experimentation determined that between the shoulder blades was the optimal position as the proximity to the sensors means the wired connections on the vest are minimal, which in turn reduces a potential source of failure. The location of the sensors and processing unit also had to account for the physical nature of the work (which might include tree climbing, carrying heavy equipment, bending and digging etc.)

Participatory design sessions were run with several groups of forestry workers along with their families and community members. These were intended to explore the following:

- How would the workers feel about being monitored using wearable technology?
- What type of personal data was it acceptable to collect?
- What sort of data and feedback would contribute to their safety?
- Who should the data be shared with and how?

Once we had gathered this information it was used in conjunction with the technical requirements to develop the full wearable eco-system.

A prototype was developed based on a wearable undergarment (dubbed the ‘smart vest’), which would be worn under any other clothing or protective gear against the workers’ skin (see Figure 2). The vest has a chest strap heart-rate monitor which is attached to the elasticated section of the vest at chest height. This ensures movement of the monitor is restricted (to prevent loss of skin contact and ‘noise’) but comfort is better than just using a heart-rate band due to the integration with the fabric. Galvanic skin response (GSR) sensors are attached to the shoulder area where the previous experiments demonstrated good skin conductance and similar measurements to standard finger sleeves provided with GSR sensors. Wiring from both sensors is run through the back of the vest to the pocket where the processing unit can be stored. Once the processing unit is in place the GSR sensors can be positioned on the body.

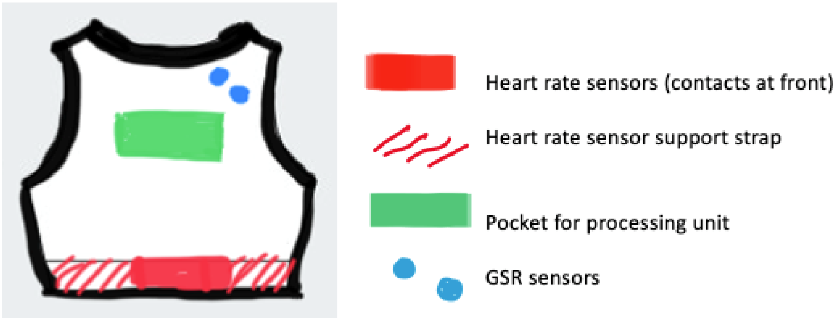

Figure 2: Smart vest prototype (back view)

The initial design included a hard box (3D printed to size) to enclose the processing unit and batteries. However, the current prototype for the unit consists of the following: Raspberry Pi Zero connected to a Spark Fun ESP32 board; SparkFun heart rate monitor; Grove GSR sensor; Adafruit real-time clock module; MPU-6050 Accelerometer/Temperature Sensor; Adafruit Powerboost 500C; 2 lithium batteries (see Figure 3). The overall size requires a hard, outer casing that is too big to be worn without discomfort. While the printed outer shell will be a suitable solution once we have a custom programmable circuit board (PCB) printed, for the current prototype we replaced this with a neoprene sleeve with thick plastic inserts to protect the electronic components.

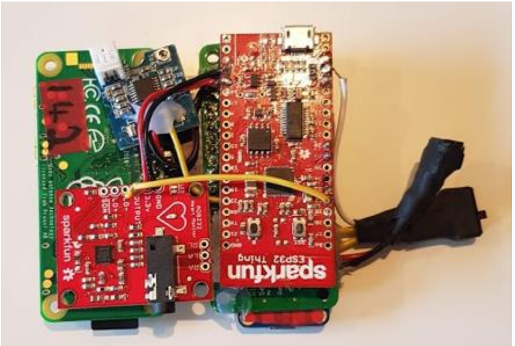

Figure 3: Processing unit

Initial evaluations were performed by the research team which followed the earlier experiments around data collection and correctness (compared to secondary data collection wearables). These included tests for various physical activities such as running, climbing, driving etc. Testing also included wearing the vest for 8-10 hours a day to ensure comfort. Once we were satisfied that these initial experiments had demonstrated appropriate levels of robustness, accuracy and comfort the next step was to evaluate the prototype with forestry workers. We discuss this next.

Prototype Evaluation

Having demonstrated that the requirements were satisfied in laboratory and simulated activity settings, we next moved on to study the prototype in a real-world forestry setting. The study was intended to test comfort and durability of the sensors and vests during a typical working day in the forest as well as analyse positioning of the sensors and processing unit with respect to accuracy of data collection and ability to withstand typical work activities.

Three smart-vest prototypes were built and along with a base-station unit were deployed with three forestry workers for a period of one week. The study was conducted by a single researcher, and the study plan consisted of the following: on the first day provide the participants with written information about the project and ethical consent process, answer any questions participants have and obtain their written consent; each morning provide the workers with the vests, ensure connectivity between sensors and the processing unit and between the processing units and the base station; at the end of each working day collect all equipment from site, run through a short questionnaire with the workers regarding comfort and any potential problems that may have arisen; each evening check equipment for damage and repair as necessary, check data uploads, recharge all battery packs ready for the next day, wash and dry each of the vests.

Results

The data collected over the course of the five-day study is shown in Table 1. W1, W2 and W3 are the three forestry workers taking part in the study. For each category of data, we indicate whether/how much data was collected for day 1-5. An ‘x’ indicates no data collected, ‘f’ indicates a full day of data was collected and ‘p’ indicates data was collected for part of the day. The most striking observation from Table 1 is that there is no data category that was collected in full over the 5-day course of the study, there are multiple reasons for this.

Table 1: Data collected over five days for three workers

Workers Days	**HeartRate/HRV 1 2 3 4 5**	**GSR 1 2 3 4 5**	**Accelerometer 1 2 3 4 5**
W1	p x x x x	p x x x x	p x x x x
W2	p x p p f	p x p x x	p x p f f
W3	p f x p p	p p p f p	p f p f p

Worker 1 (W1) has partial data collected on day 1 only. After donning the smart vest and commencing work, one of the first things the worker did was lift up a large coil of rope required for the day’s task and throw it over his shoulder to carry it. The full weight of the rope impacted directly on the pouch containing the processing unit causing irreparable damage. The remainder of the study was, therefore, conducted with W2 and W3 only.

Worker 2 (W2) has a mixture of full/partial/none across all days, with full data for only HR/HRV on day 5 and Accelerometer data for days 4 and 5. The heart-rate monitor proved to be subject to considerable movement (and therefore lack of skin contact or correct placement) throughout the day. This was dependent on activity and worker adjustment (moving the vest for comfort etc.). Typically, the HR data would be collected satisfactorily for 1.5 – 2 hours, then would be disrupted for 0.5 – 1 hour and then revert to successful collection. On day 2, as W2 placed the processing unit into the pouch they dislodged the battery connection and therefore there was no data collected on that day. Day 4 was extremely wet with heavy rain throughout the work period. The GSR sensors proved not to be water resistant and W2’s shorted out part way through the day and could not be repaired for Day 5.

Worker 3 (W3) experienced the same problems with the heart-rate monitor as W2. In addition, on day 5 their physical activity resulted in the on/off switch for the processing unit being toggled to the off position causing all data collection to stop part-way through the afternoon.

The accelerometer data proved to be the most reliable, primarily due to the location of the sensor within the processing unit rather than attached elsewhere on the vest. On all occasions where the accelerometer stopped recording data the unit itself had ceased to record anything due to battery connectivity or switch problems.

At the end of day one, the workers reported that while the vest was not uncomfortable, they were aware of it and also the sensors. However, by the end of day 2 they had become accustomed to wearing it and so had stopped noticing it.

Discussion

It is clear from the results in Table 1 that more work is required on the technical aspects of the solution to improve robustness. Some of these are related to the technology used for the prototype (a collection of PCBs and attached sensor boards), which will be improved once the custom-built solution is created (the smaller footprint of this will also allow a hard case enclosure). In addition the choice of sensors need to be revisited to ensure all equipment is water resistant.

We now consider the ergonomic considerations derived from the study in terms of the numbered requirements given above. The worker comments cited above suggests that the prototype meets the requirements of being non-intrusive (1), comfortable (2) and lightweight (3). The processing unit is compact (4), but not small enough in its current form to allow for a hard enclosure. This is something that can be improved once we are working with custom built hardware rather than relying on joining together multiple PCBs and sensors. The prototype failed to meet the durability requirement (5) with multiple points of failure, e.g. batteries became disconnected, on/off switches were toggled, sensors were not water resistant etc. This needs to be the primary focus of the next iteration of the prototype, as a solution that works only part of the time or continually needs repairing or replacing is not viable. The cost of the current prototype (6), including the vest and all of the sensors is around NZ$250 (GBP126). This is too expensive, considering a typical forestry crew may consist of 10-30 workers, then the entire solution (including central base station) will need to come in at less than $100 per worker in order for it to be financially viable. Again, some costs will be reduced once we move to custom made hardware which can be mass produced at a much lower cost than purchasing multiple boards. In addition, the vests themselves will need to be manufactured (with integrated sensors) rather than manually constructed like the prototype. Cost efficiency for this will come with volume and therefore final costs will need to be calculated once all of these components have been finalised. The vests in their current form factor are easily washed (7) as all of the hardware is removable, this will need to be retained for the final form factor.

Conclusion

In this paper, we have described the evolution and evaluation of a smart vest for use in the forestry environment to collect personal metrics from workers. There are a number of crucial ergonomic factors that must be considered when developing wearable technology for rugged work environments. Here we have evaluated practical considerations such as comfort, durability etc. but also outlined the need to consider data management, privacy and ownership as important factors to be included.

The evaluations of the prototype show that the current form factor of the vest is suitable and it is an acceptable solution for forestry workers that can be used without interfering with worker comfort or work activities. However, there is still work to be done in order to satisfy requirements such as robustness and cost.

While there have been previous proposals for developing wearable technology for rugged worksites, these are rarely designed and evaluated with intended users in-situ. We have demonstrated in this paper the importance of ergonomic considerations of real-world environments of use and engagement with end users.

References

Bowen, J., Hinze, A., Cunningham, S. J. & Parker, R. (2015). Evaluating low-cost activity trackers for use in large-scale data gathering of forestry workers. Proceedings of the annual meeting of the Australian special interest group for Computer Human Interaction, OZCHI 2015, Parkville, VIC, Australia. Pages 474-482.

Bowen, J., Hinze, A., Griffiths, C., Kumar, V. and Bainbridge, D. (2017). Personal data collection in the workplace: Ethical and technical challenges. Proceedings of the 31st International BCS Human Computer Interaction conference, Sunderland, UK.

Darpa (2014). Warrior Web project archive. Last accessed October 5th, 2020. https://www.darpa.mil/program/warrior-web

D'innocenzio, A. (2015). Target is offering a new perk to its 300,000 workers. Associated press article, Business Insider, https://www.businessinsider.com/ap-target-developing-healthier-habits-hands-workers-fitbits-2015-9?IR=T, last accessed October 10th, 2020.

Edirisinghe, R., & Blismas, N. (2015). A prototype of smart clothing for construction work health and safety. Proceedings of CIB W099. Benefitting workers and society through inherently safe(r) construction, 1-11. EEI Publishing, Downpatrick.

Griffiths, C., Bowen, J. and Hinze, A. (2017). Investigating wearable technology for fatigue identification in the workplace. INTERACT (2) 2017: 370-380.

Hazarika, P. (2016) Implementation of smart safety helmet for coal mine workers. In 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), Delhi, 2016, pp. 1-3.

Hockey, R & Ebrary, I. (2013). The psychology of fatigue: Work, effort and control. Cambridge University Press.

Hoyt, R.W., Buller, M.J., Gunga, H., Werner, A., Sattler, F., Koch, J., Nevola, V.R., Ledderhos, C. and Valk, P. (2010). Real-Time physiological and psycho physiological status monitoring, final report of task group HFM-132 NATO.

Ministry for Primary Industries, NZ (2019) Forestry health and safety online resources for forestry NZ, https://bit.ly/2HGnauQ last accessed September 2020.

Sinha, A., & Vyas, H. (2018). Monitoring health and safety of oilfield workers through wearable technology. Society of petroleum engineers. doi:10.2118/190552-MS

Safetree NZ (2016). Fatigued? Or fit for work? Health and safety at work online resources, https://safetree.nz/wp-content/uploads/2016/11/Fatigued_-Or-Fit-for-work_-.pdf. Last accessed September 2020.

Young, E. (2015). Do you want your company to know how fit you are? BBC Business News, https://www.bbc.com/news/business-33261116. Last accessed October 16th, 2020.