European Agency for Safety and Health at Work

CASE STUDY

SMART DIGITAL SYSTEMS FOR IMPROVING WORKERS' SAFETY AND HEALTH:

SMART HEADBAND FOR FATIGUE RISK-MONITORING

1 Introduction

Smart digital systems and technologies entering EU workplaces are reshaping work environments for workers and employers alike. Innovations in smart wearables, exoskeletons, artificial intelligence (AI), machine learning (ML), internet of things (IoT), virtual and augmented reality (VR and AR), among others, are giving new opportunities for preventing and responding to workplace risks.

As part of EU-OSHA's occupational safety and health (OSH) overview programme (2020-2023)[1], EU-OSHA has examined the challenges and opportunities of smart digital tools and monitoring systems for improving workers' safety and health. These systems, leverage digital technology to collect and analyse data in order to identify and assess risks, prevent and/or minimise harm and promote OSH.[2] EU-OSHA has categorised such systems into proactive (preventive) and reactive, albeit acknowledging the potential overlap between the two.[3] EU-OSHA further provided an overview of the risks and opportunities associated with these systems[4] and explored the workplace resources that could ensure their safe and healthy use.[5]

In order to investigate the practical implementation of smart digital tools and new OSH monitoring systems for improving workers' safety and health, EU-OSHA has developed a number of case studies. This set of case studies includes both cases of smart digital systems at the level of design/development and cases of companies implementing the systems. The case studies accordingly investigate aspects related to the design/development stage and to the implementation stage. OSH aspects including worker's involvement was considered in all case studies taking into account the type of case study. Further all case studies look at possible drivers, barriers and success factors for safe and effective implementation.

To develop these case studies, apart from desk research, a number of interviews with key informants were conducted, including workers' representatives, safety officers, employers and representatives of industry associations. In addition, at company level, up to five interviews were conducted with operators, data protection officers, health and safety engineers, managers, work councillors and technology officers. The interviews had a duration of 1-1.5 hours each and were performed in the participants' native language, if possible, or alternatively in English, an interview guide, while the results of the interviews were anonymised. The case studies referring to designers' results do not contain detailed information on workplace implementation, as there has been limited collection of information from companies in which the systems are installed.

In total 15 cases were identified, and preliminary information was collected for these through a questionnaire, hereafter, nine of them were further developed into case studies.

[1] For more information, see: osha.europa.eu (n.d.) Digitalisation of work. Available at: https://osha.europa.eu/en/themes/digitalisation-work

[2] EU-OSHA (2023). Smart digital monitoring systems for occupational safety and health: uses and challenges, https://osha.europa.eu/en/publications/smart-digital-monitoring-systems-occupational-safety-and-health-uses-and-challenges

[3] Ibid.

[4] Ibid.

[5] EU-OSHA (2023). Smart digital monitoring systems for occupational safety and health: workplace resources for design, implementation and use, https://osha.europa.eu/en/publications/smart-digital-monitoring-systems-occupational-safety-and-health-workplace-resources-design-implementation-and-use

2 Description of the smart digital system for OSH

2.1 General company description (developer)

This international mining company has partnered with mining companies worldwide for over 40 years. In 2021, the company acquired a commonly used fatigue-monitoring wearable device: a smart headband for fatigue risk-monitoring, which added fatigue-monitoring to the company's safety services. Safety is of paramount importance at mines and other industrial sites where workers perform long hours of repetitive work while paying close attention to their surrounding environment. The developed smart system assesses real-time fatigue levels, while monitoring for oncoming fatigue events that create safety hazards, and is used globally, primarily in mining, trucking and other heavy equipment-related industries. It provides real-time alertness measurements that enable drivers to manage their fatigue proactively. Moreover, it can eliminate the risks of microsleeps by providing early-warning alerts and fatigue risk alarms, combined with the centralised dashboard.

2.2 Description of the digital system for OSH

2.2.1 What is the fatigue-monitoring system for?

Fatigue is a growing problem in working life. According to different data and sources, a fatigued worker has an approximately 62% higher risk of accidents resulting from human errors due to tiredness-related performance decline.[6] According to the Australian State of Victoria Department of Health, fatigue symptoms can be categorised into three sets: physical, mental and emotional.[7]

Table 1: Physical, mental and emotional symptoms of fatigue

Physical symptoms	Mental symptoms	Emotional symptoms
Slowed reaction time	Difficulty concentrating	Social withdrawal
Lack of energy	Attention deficiency	Lack of motivation
Staggering while walking	Slow reactions	Irritability
Eyelids feeling heavy	Problems communicating	Low morale
Drowsing off	Making mistakes	Emotional sensitivity
A small nap was taken	Weak decision-making	Unwillingness

Source: Department of Health, State Government of Victoria, Australia

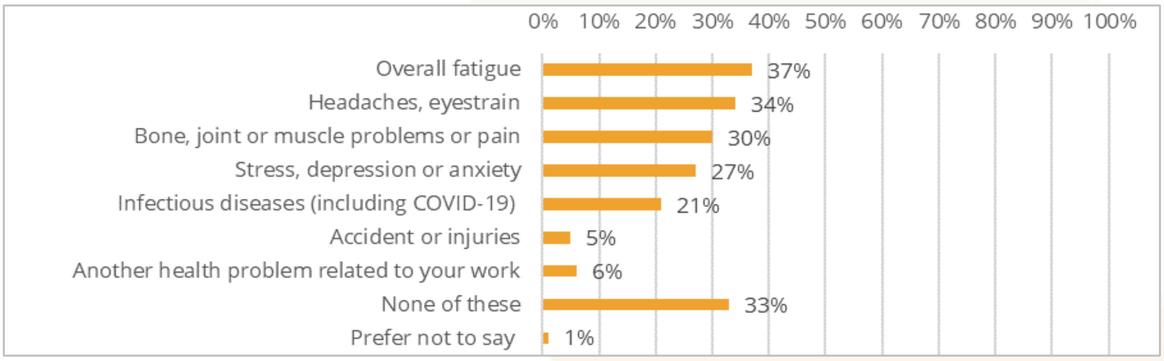
The above categorisation is relevant to occupational safety. Fatigue – for an individual and complex human factor – can be easily overlooked, disregarded or underestimated when examining the root causes of workplace incidents or accidents. It can be a direct or indirect risk factor leading to or enabling an accident. The relationship between fatigue and errors in vigilance, perceptual motor skills, and attention is well known. Categories of work that require special consideration in fatigue risk management are shift work, on-call work, travel work and seasonal work.[8] Fatigue is a significant risk factor in industries where alertness is critical (for example, vehicle transport, maritime transport, air transport, air traffic control and industry or heavy transport), as well as where complex tasks are

[6] If P&C Insurance (2022). Fatigue in work-related accidents, https://www.if-insurance.com/large-enterprises/insight/risk-consulting-magazine/risk-consulting-2022-3/fatigue-in-work-related-accidents
[7] State of Victoria (2023). Fatigue, https://www.betterhealth.vic.gov.au/health/conditionsandtreatments/fatigue
[8] Safe Work Australia (2013). Guide for managing the risk of fatigue at work, https://www.safeworkaustralia.gov.au/system/files/documents/1702/managing-the-risk-of-fatigue.pdf

performed around the clock with risk of significant injury, accident (including fatality) or property damage.[9]

EU OSHA research highlights the importance of this factor: OSH Pulse, its series on occupational safety and health in post-pandemic workplaces, analyses the mental and physical health stressors of over 27,000 employed workers in all EU Member States, plus Iceland and Norway.[10] According to data gathered by EU OSHA, **overall fatigue is the most-cited health issue caused or made worse by work (37%)**, followed by headaches and eyestrain (34%), and then bone, joint or muscle problems or pain (30%).[11] In 17 of the 27 EU Member States and Iceland, overall fatigue is the work-related health problem listed most frequently (or joint most frequently).

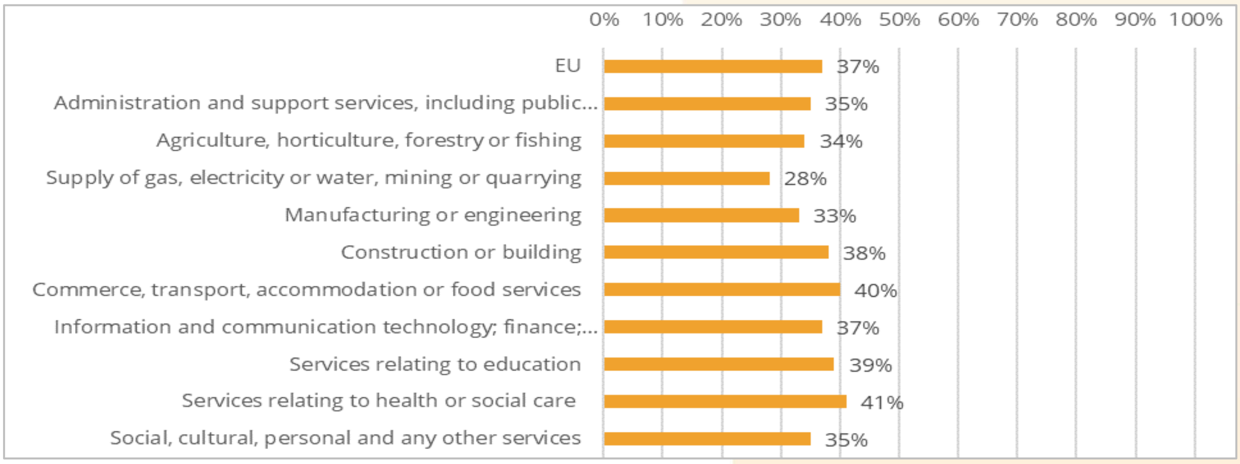
Figure 1: EU OSHA survey question: In the last 12 months, have you experienced any of the following health problems caused or made worse by work (%, by sector of activity)



Source: EU OSHA, 2022[12]

In the economic sectors, respondents working in commerce, transport, accommodation or food services (40%) and in health and social care (41%) tend to be somewhat more likely to report having experienced overall fatigue. A high rate was recorded also in services related to education (39%) and construction or building (38%).

Figure 2: EU OSHA survey question: In the last 12 months, have you experienced any of the following health problems caused or made worse by work (%, by sector of activity)? Indication of: OVERALL FATIGUE



Source: EU OSHA, 2022[13]

[9] If P&C Insurance (2022). Fatigue in work-related accidents, https://www.if-insurance.com/large-enterprises/insight/risk-consulting-magazine/risk-consulting-2022-3/fatigue-in-work-related-accidents

[10] EU OSHA (2022). OSH Pulse - Occupational safety and health in post-pandemic workplaces, https://osha.europa.eu/en/facts-and-figures/osh-pulse-occupational-safety-and-health-post-pandemic-workplaces

[11] EU OSHA (2022). OSH Pulse - Occupational safety and health in post-pandemic workplaces. Flash Eurobarometer, https://osha.europa.eu/sites/default/files/Eurobarometer-OSH-in-post-pandemic-workplaces_en.pdf

[12] Ibid.

[13] EU OSHA, 2022, OSH Pulse - Occupational safety and health in post-pandemic workplaces. Flash Eurobarometer, https://osha.europa.eu/sites/default/files/Eurobarometer-OSH-in-post-pandemic-workplaces_en.pdf

2.2.2 How does the fatigue-monitoring system work?

The technology developed for the smart headband contains an algorithm to **detect microsleeps** and thereby **eliminate fatigue-related or fatigue-induced accidents**. The fatigue-monitoring technology has been tested on precision and effectivity to provide real-time alertness measurements, enabling its users to manage their own fatigue proactively. The technology helps to effectively manage fatigue and provides alarms to ensure the workforce is safe.

To that end, the system anticipates risks and improves safety reporting in work environments like trucking, aviation, freight and maritime. However, the developing company's headband is used primarily in mining, where specific working conditions are perceived as contributing to fatigue, and therefore, raise safety concerns. These working conditions include a lack of natural light, elevated temperatures, cramped workspaces, and air quality issues such as high humidity, particle pollution, reduced oxygen levels and mine gas contamination.[14]

The system's technology is based on **brainwave processing.** The Smart fatigue risk monitoring headband uses **electroencephalogram technology which processes information from brain waves**. The electroencephalogram is a direct source for measuring fatigue and vigilance in real time and allows early detection of fatigue. The technology is designed to be used by individual workers. Ultimately, workers are best able to discern their own fatigue, so the technology has been designed to ensure that individuals are empowered to do so. Alerts, reports and individual profiles will inform each user when they are at risk and at which times of the day their risk is most significant. The basic element of the fatigue-monitoring system is a 44-gram, battery-powered wearable band that is worn on the head, secured with an elastic strap. The band can be clipped into a baseball cap, turban, hard hat or other headwear the end users might be wearing.

Using an algorithm, the system analyses the frequency data to determine the user's fatigue or alertness level. These data are then transmitted to a mobile application, which in turn, uploads them to a cloud platform. An in-cabin display, or any smartphone, is mounted in the vehicle's cab to provide **immediate feedback and alerts to the vehicle driver**. **Centralised monitoring** is provided via a cloud-hosted analytics suite, which can also issue SMS and email alerts to line supervisors and management. Initially, data are stored on the mobile application, and then the system employs databases for real-time fatigue-monitoring. The tool is proactive because it can 'read' from the brain and turn this into analytics, unlike more reactive tools based on external signs of fatigue (like camera-based systems).

Figure 3: Three steps to use the fatigue-monitoring system

Step 1 Attach the band to your headwear.	Step 2 App installation and connection via Bluetooth. Fatigue tracking.	Step 3 Transfer of collected and processed data. Cloud-hosted analytics.
		
▪ The band uses state-of-the-art brainwave technology to determine worker alertness.	▪ Is installed on device(s) like phones. ▪ Has Bluetooth connectivity.	▪ The system gathers a comprehensive range of fatigue and operational data.

[14] Butlewski, M., Dahlke, G., Drzewiecka, M., & Pacholski, L. (2015). Fatigue of miners as a key factor in the work safety system. *Procedia Manufacturing*, *3*, 4732-4739, https://doi.org/10.1016/j.promfg.2015.07.570 [Available at: https://www.sciencedirect.com/science/article/pii/S2351978915005715/pdf?md5=5f13fbd0c1e6ee523b5e2d60a8e77dd1&pid=1-s2.0-S2351978915005715-main.pdf]

Step 1 Attach the band to your headwear.	Step 2 App installation and connection via Bluetooth. Fatigue tracking.	Step 3 Transfer of collected and processed data. Cloud-hosted analytics.
▪ Eliminates microsleeps with accurate fatigue measurements.	▪ Fatigue level 'speedometer' view provides **real-time alerts** to prevent microsleeps before they happen. ▪ Screen adjusts for night and daytime settings. ▪ Alerts user when the cap is fitted incorrectly. ▪ Is available in different languages. ▪ Allows progress tracking to support wellness initiatives.	▪ Centralised dashboard provides many analytics, reporting and actionable insights, including company-wide trend analysis based on fatigue risk and individual worker assistance. ▪ Cloud-hosted analytics suite gives supervisors access to real-time data that can assist with shift structures.

Moreover, the smart headband informs workers about fatigue levels. The alert scale has five levels (1 to 5). The level system is a spectrum of varying degrees of alertness and fatigue risk, in which level 1 represents maximum alertness, while level 5 indicates clinical sleepiness. Typically, users respond positively to orange alerts, self-managing their fatigue by adjusting their posture or taking a break. Level 4 signifies a higher level of fatigue risk; it is the last chance for the user to self-manage. If the user remains at level 4 for 2 minutes, the device triggers an alarm back to the employer, and company fatigue management policies, such as pulling over, may be employed. The employer determines the critical point for intervention. Level 5 indicates the user is clinically asleep; even though it is incorporated into the scale and the algorithm, the product does not show the fifth level, as the user will never reach this level.

In addition, the technology further enables vehicle tracking through Geographical Positioning System (GPS) and is part of a web-based application. This solution allows customers to see an overview satellite map and verify where all their assets are moving; overlaying them with fatigue results, thus making it possible to locate the vehicle and the worker positions in real time.

Figure 4: Cartoon-style representation of the headband for fatigue risk-monitoring

The technology also aimed to ensure diversity and inclusion, by granting broad access to the protection and OSH to a wide range of potential users. It is essential to have a data set incorporating diversity not only for algorithmic accuracy but also for independent validation of the system. To fulfil this the team included brainwave data from individuals representing diversity in e.g. biological sex and age (from 16 to 95) in the system's data set. In terms of hardware design, the system is adaptable to regional variations and user preferences. The fatigue-monitoring system can be worn independently or incorporated into a baseball cap. The goal is to maximise flexibility in terms of comfort and design while maintaining a generic and universally applicable algorithmic foundation.

2.2.3 Technologies employed in the fatigue-monitoring system

As previously outlined, the wearable band relies on EEG sensors to assess an individual's fatigue level. An EEG sensor is an electronic device that detects and measures electrical signals generated primarily by large groups of neurons near the brain's surface. It can provide valuable insights into brain activity over time.[15]

Figure 5: Technologies employed by the fatigue-monitoring system

EEG	Bluetooth	Internet of things	Cloud-based analytics	GPS
State-of-the-art EEG brainwave technology monitors and measures workforce fatigue.	Bluetooth transmits the collected and processed data to devices (smartphones, tablets, laptops, and so on).	Internet of things (IoT)-enabled sensors on the band transfer data to the app and from it to cloud-based software (wearable technology).	The system collects and analyses data to help manage fatigue and implement preventive accident measures.	The system enables GPS satellites to collect location data and transmit it to the vehicle trac.

2.3 Examples of use

The system is currently used extensively in sectors employing human-operated traffic controllers, like maritime, aviation, railway and over-the-road transport, helping workers to self-manage their fatigue risk before falling asleep.

As part of its development process in Australia, the tool underwent early-phase tests and trials with different Australian mining companies to validate its viability. In 2012, one of the first use cases of the system to integrate the technology into **its existing Fatigue Risk Management System framework** implemented the tool as a mandatory tool for operators of the haulage fleet (83 rear-dump haul trucks). The fatigue-monitoring system provided real-time fatigue alarms to a central control room, triggering safety interventions. This has led to **a significant reduction of fatigue incidents to almost zero.**[16]

3 System implementation: drivers and barriers

3.1 Motivators and goals

In the early 2000s, truck manufacturers sought fatigue technologies for the mining industry. Their assessment of the existing technology was that nothing was fit for purpose and no solutions were entirely suitable. As fatigue is a significant and urgent problem in mining, the challenge was to overcome

[15] Soufineyestani, M., Dowling, D., & Khan, A. (2020). Electroencephalography (EEG) technology applications and available devices. *Applied Sciences*, *10*(21), 7453, https://doi.org/10.3390/app10217453

existing limitations of fatigue-monitoring technologies, that led to the development of an algorithm that could be translated into software development for monitoring vigilance, alertness and fatigue levels.

In 2004, the technology was refined via a research consortium with universities and industry partners, including equipment manufacturers and mining companies. Furthermore, the fatigue-monitoring technology has been independently validated by universities.

The technology also aimed to **ensure diversity and inclusion by granting broad access to the protection and OSH to a wide range of potential users**. For genetic diversity, the team included brainwave data from individuals representing **diversity in e.g. biological sex and age (from 16 to 95)** in the system's data set. This data set diversity is essential not only for algorithmic accuracy but also for independent validation of the system. In terms of hardware design, the system is adaptable to regional variations and user preferences. The fatigue-monitoring system can be worn independently or incorporated into a baseball cap. The goal is to maximise flexibility in terms of comfort and design while maintaining a generic and universally applicable algorithmic foundation.

3.2 Drivers

The fatigue-monitoring system predicts fatigue rather than reacts to a fatigue event, **improving safety and prevention**. Compared with the more common camera-based solutions, this system offers proactive risk management and accurate hazard detection. The system also improves **worker health and well-being** by **ergonomically monitoring** stress and fatigue. **Worker empowerment** and **personal safety awareness** are other significant drivers. By providing immediate feedback to workers about their fatigue, the system encourages self-awareness and proactive behaviour.

From an operational point of view, the fatigue monitoring system leads to efficiency, as the GPS feature enables a company to verify the location of their equipment while monitoring fatigue. In case of an equipment-related issue, this would lead to reduced downtime, and thus, more **effective resource allocation**.

The interviews confirmed desk research findings, that **workers' in involvement and acceptance are major drivers** for effective system implementation: **provision of information to workers on system operation, data collection and purpose of use** promote workers' engagement.

The tool developer has designed and developed a **detailed, step-by-step plan for system implementation.** This elaborate approach and change management strategy are key factors for ensuring successful implementation of the tool. Initially, the engagement strategy entails establishing **communication with the client company at all organisational levels, ranging from top leadership to the workers who will use the band**. This includes consulting, briefing, educating, workshops, individual consultation with workers, and identifying individuals who can exert a positive influence on their peers. More specifically, the fatigue-monitoring system team holds weekly meetings with clients to track progress and assign tasks, while maintaining communication through calls and emails for urgent matters.

Moreover, employers (clients) who have fully implemented the product actively provide feedback, shaping the future direction of the fatigue-monitoring system. These engaged clients interact with the system developer through account representatives or sales teams. Clients' feedback remains integral to the continuous development of the system, and play a vital role customers in introducing new ideas and suggesting improvements to the safety solutions. Rather than a one-size-fits-all strategy, the system developer adopts a **tailored and personalised approach** to its clients. This approach allows product implementation to be customised to the needs of end users and other workers, in terms of both the wearable design and the various stages of the implementation process. Moreover, the training sessions are tailored to the goals of each organisation adopting the solution, and they focus on the most applicable and useful information for each operation site.

The goal of the change management approach is to enhance the health and safety culture in organisations implementing the solution. This approach aims to help organisations prioritise health and safety and promote the importance of fatigue management among their operators. Effective fatigue management involves encouraging workers to report fatigue and take breaks, rather than penalising them. For this to be successful, a robust health and safety culture is necessary. Moreover, a change management approach brings about **engagement,** as involving workers in safety practices through technology can increase their commitment to a workplace. Table 2 summarises the drivers of the fatigue monitoring system for companies and for various job roles.

Table 2: Drivers of the fatigue-monitoring system for company-client workers

Role	Drivers
Management	▪ Improved labour standards and safety ▪ Proactive risk management ▪ Effective resource allocation
OSH specialists	▪ Accurate hazard detection ▪ Ergonomic monitoring ▪ Change management and training
Workers	▪ Improving health and wellbeing ▪ Empowerment and personal safety awareness ▪ Increased engagement with the workplace ▪ Engagement in system implementation

2.3 Barriers

There have been several barriers and challenges to adopting the smart headband for fatigue risk monitoring. However, measures are in place to address these challenges effectively.

Compliance with stringent **data privacy laws** (for example, GDPR) can be challenging, especially regarding the collection and use of personal data. Measures and policies of effective data privacy can successfully remove this barrier. **No personal data or usernames are used in the data transmission process from the touchscreen to the cloud-based software.** The only information conveyed is the serial number of the band and the corresponding fatigue level. To identify whose data are being received, users must associate the band's serial number with their name, and this association is conducted in a secure environment, never traversing the internet. As a result, user data remain fully protected and confidential, even against **cybersecurity risks**. Even in the unlikely event of a third party gaining access to this data within a secure network, they would find only a serial number and a fatigue score. **This data privacy approach is also in line with existing legal frameworks.** The product's configuration and data storage are adapted to meet the specific privacy regulations in various jurisdictions where the solution is implemented. Based on the interview findings, the system developer has not come across any privacy-related OSH regulations directly impacting the existing fatigue-monitoring system.

Another barrier to implementing the system is **client resistance, due to the traditional approach** in mining businesses to adopting wearable and cloud-based technologies. Unlike other companies chiefly developing reactive technologies (cameras and video monitoring of workers), the company's technology implementation system requires that workers be familiarised with the product and trained in the use of the technology (use of the system, data analysis, creation of safety protocols, and so on). Hence, the system comes with **training costs** and a commitment of several weeks for workers and health and safety professionals.

To overcome this challenge, the company has invested a great deal of effort in helping customers recognise the value of fatigue-monitoring, including demonstration of the functional capabilities that can be achieved through technologies. Additionally, the system can be tailored to meet the specific needs of individual clients (employers), ensuring seamless integration of these features into the overall monitoring and analytic system.

The barrier of client resistance is partially related to worker resistance, as discussed below under OSH challenges. Worker acceptance of the wearable can be hindered by concerns about the extent and types of data the device collects and processes. Specifically, end users may worry that the system is extracting extensive information from their brain waves. However, independent auditors including universities and hospital institutes validated the technology and confirmed that the only information it is authorised to collect and cover from the brain wave is the fatigue level.

Similarly, users fear being identified for any perceived lapses in performance or health issues. However, the implementing company (employer) has stringent measures in place to ensure that personal information remains entirely confidential. Workers' resistance also stems from anxiety about job repercussions, as workers fear facing disciplinary action. However, interviewees noted that monitoring technologies should not be used for punitive reasons; such an approach leads to low acceptance among workers. Hence, they underlined that the system focuses on improving overall operations and health, since that is the intended purpose. Workers' representatives could play a role in ensuring that the system is not used for other purposes.

Building trust is crucial for overcoming worker resistance to the solution

The system development team encourages the client to put their commitments and assurances in writing, so end users feel sure that the system will not be used against them. They identify the most resistant workers and work on building trust through frequent interactions and training sessions.

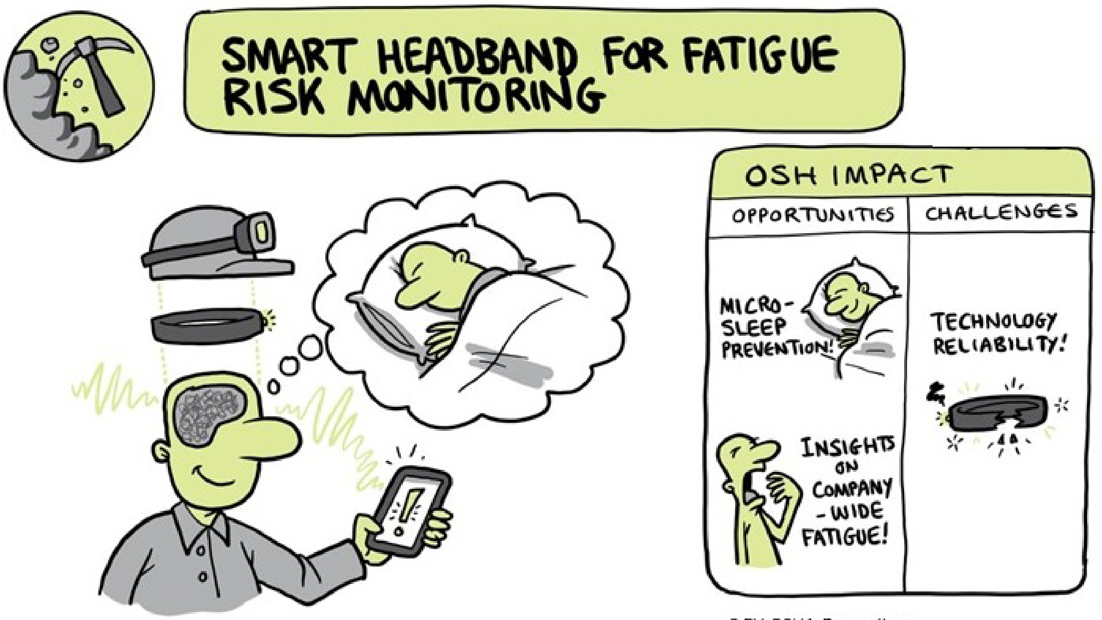
Regarding technical challenges, **connectivity** can be a barrier. This safety system is typically required in areas with limited internet connectivity like remote mine sites. In such environments, **providing quick local feedback to operators and uploading data to the cloud for central monitoring can be a challenge**. Overcoming potential connectivity barriers and ensuring the system's robustness and reliability in these conditions is a priority for the company. To overcome connection limitations in remote environments, the fatigue-monitoring system has the capability to transmit data in several ways. These include utilising the site's Wi-Fi or local area connection, connecting to a long-term evolution network, and even utilising satellite communications, in some cases.

Other barriers include high **cost and investment,** as the purchase, deployment and maintenance of wearable systems require significant investment. Regular updates, calibration and battery replacements add to the **ongoing costs**. Additionally, managing and analysing the large volumes of data generated by wearables can be complex and resource intensive.

4 OSH impact

As mentioned above, the fatigue-monitoring system is actively utilised in sectors related to human traffic (maritime, aviation, railway and over-the-road transport), mitigating the most prevalent work-related vehicle accident injuries in these work environments. The tool discreetly examines workers' biological condition and employs up-to-date technology, offering a significant opportunity to improve safety by managing OSH risks specific to the mentioned industries. This section addresses the opportunities and challenges of the fatigue-monitoring system related to OSH.

Figure 6: Headband for fatigue risk-monitoring: opportunities and challenges for OSH



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4.1 Opportunities

The fatigue-monitoring system presents many OSH opportunities regarding safety and security, as the system predicts fatigue rather than reacting to a fatigue event. In that way, the system promotes **proactive safety measures, enabling quick action to mitigate risks before they result in injury**. In addition enables **real-time hazard detection** with immediate alerts, focusing solely on fatigue without monitoring exposure or ergonomics. Another OSH opportunity of the system is proximity and location tracking for **collision avoidance**. The system alerts workers and machinery operators when they are too close to each other, preventing accidents.

Moreover, the **fatigue-monitoring system encourages individuals to understand and improve their personal wellbeing**, including dietary habits, sleep schedules and exercise routines. When used effectively, this broader opportunity extends beyond workplace safety to improve workers' health and quality of life. **The system provides significant insights into underlying health issues of individuals that they may be unaware of**. The overwhelming majority of users at a given workplace do not get fatigue alarms, and a few represent most of the fatigue alarms; between 4% and 7% of any workforce represent 75% of all risk events. Thus, end users may discover sleep apnoea or other conditions they would never have known needed treatment.

Wearables can function as personal safety reminders, providing feedback to workers about their safety behaviours. Implementing companies (clients) have observed that the fatigue-monitoring system not only ensures a safer workforce but also fosters **heightened alertness among workers**. As real-time feedback on fatigue risk prompts individuals to make incremental lifestyle adjustments, it collectively contributes to an overall boost in workforce alertness and increased productivity.

From an OSH management point of view, the system's data-driven insights can **improve workplace design, organisation, and protocols or interventions**. For example, different rosters, schedules, and working or resting times can be optimised in combination with different locations and situations. Another opportunity is **trend analysis**; identifying patterns in hazardous working conditions and behaviours that lead to fatigue can inform long-term safety strategies.

Most clients (employers) do not perceive the system as a one-time solution but as a means for **constant OSH improvement**. Some clients have even implemented overall fatigue risk-management programmes, with the fatigue-monitoring system serving as a valuable component. As incident rates decrease, customers expand their use to cover more areas and vehicles. Nevertheless, it is crucial for the system to be seamlessly integrated into the core OSH management structure and culture of a given implementing company.

Figure 7: Identified fatigue-monitoring system opportunities

OSH Opportunities

- **Proactive safety measures.** Predicting fatigue and enabling quick action to mitigate risks before they result in injury.
- **Real-time hazard detection.** Real-time readings of fatigue levels and transmission of information to the workplace.
- **Collision avoidance.** Alerting workers and machinery operators when they are too close to each other, thereby preventing accidents.
- **Increased workforce alertness.** Real-time feedback on fatigue risk prompts incremental lifestyle adjustments, boosting overall alertness and productivity
- **Health and wellbeing.** Improving worker health, safety and productivity.
- **Data-driven workplace design.** Improving workplace design, organisation, and protocols or interventions based on data-driven insights
- **Constant OSH improvement.** Using the fatigue-monitoring system as a means for ongoing OSH improvement and integrating it into fatigue risk-management programs.

4.2 Challenges

The system's major OSH challenge is the **psychosocial implications on worker** that could originate from the **fear on being monitored** and **data privacy.** Continuous monitoring may be perceived as invasive, leading to perceptions of overreach. Workers adopting the fatigue-monitoring system might resist wearing a headband due to the stress of being monitored. **Workers might feel micromanaged** by the system. Workers' concerns are often related to **the fear of job repercussions;** they are apprehensive about being labelled as fatigued and potentially facing disciplinary action, known in the industry also as 'get tired and get fired'. Some workers resist wearing the devices or not using them correctly, which also affects data quality and system effectiveness. **Data misuse** is another concern causing resistance: sensitive data can be accessed or used improperly by unauthorised personnel, posing significant concerns for privacy and confidentiality.

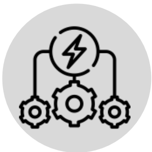
As worker resistance is also an implementation barrier the employer should put measures in place to address the concerns of the workers. The interviewees underlined that cultural and leadership factors influence the resistance level, with trust in leadership easing system adoption, particularly in industries like mining, where centralised communication is more straightforward. By contrast, industries where workers work from different worksites may face additional challenges in reaching and engaging with end users to address their concerns effectively. In some jurisdictions, **unions are involved in implementing the system** to explore the workers' concerns and alleviate fears of potential misuse of the system. Legislation and regulations that oblige employers to implement specific systems or operating practices can be a factor in strengthening occupational health and safety.

Another challenge is the **mistrust of technology**. Despite the company's efforts to ensure seamless connectivity even in remote sites, reliability issues persist, partly due to the traditional approach of mining businesses towards adopting new technologies, as discussed earlier. Regarding OSH, this reliability issue raises **the risk of undervaluing the benefits of a proactive system**. A technical executive noted that some employers perceive the fatigue-monitoring system as an investment with no return. Instead, they would rather invest financial resources in reactive technologies (for example, cameras) that do not monitor fatigue levels. However, companies implementing the technology highlight several benefits and advantages resulting from a proactive system compared to a reactive one: the former enables the prevention of incidents before they occur, and the fatigue data can be further integrated into OSH management, providing insight for preventive measures.

There are also data-security-related OSH challenges. **Cybersecurity threats** pose a substantial risk, as wearable devices and their data are prime targets for cyberattacks, potentially resulting in data breaches. While the worker's data for this particular system remain entirely confidential against cybersecurity risks, organisations should have solid measures to respond to evolving risks. **Data integrity**, ensuring the accuracy and reliability of the collected data, is also crucial for making reliable decisions based on accurate information.

Moreover, the fatigue-monitoring system has several technical challenges, as do other OSH systems. One such challenge is **device malfunction**, as wearables may fail or provide incorrect data due to technical issues, leading to potential safety risks. Limited **battery life** can also affect the continuous monitoring capabilities of the wearables. Additionally, frequent **false alarms** may lead to workers becoming **desensitised** to alerts, reducing the system's effectiveness. False alarms might also disrupt the workflow and reduce productivity. Hence, ensuring the system's accuracy is important. Lastly, wearing the hat with the band could be uncomfortable in hot weather circumstances, so its design should prioritise comfort and also take into consideration possible gender differences.

Figure 8: Identified fatigue-monitoring system challenges



Challenges

- **Worker resistance.** Workers might feel monitored, micromanaged and disciplined, and they might fear job repercussions.
- **Companies' resistance to implementing high-tech proactive solutions.** Some industries and businesses may resist wearable and cloud-based technologies, perceiving them as investment with no return.
- **Lack of regulatory frameworks.** The absence of legislation mandating the implementation of fatigue-monitoring systems is also a challenge.
- **Data security**. Wearable devices and their data can be targets for cyberattacks, risking data breaches. It is also important to ensure the integrity of the collected data.
- **Technical issues**. Potential device malfunctions, limited battery life, and false alarms might affect the effectiveness of the system.
- **Comfortable design**. The design of wearable devices must prioritise comfort, especially in hot weather.

5 Takeaways for development and implementation

This section outlines the primary insights for developing and safely implementing the smart headband for fatigue risk-monitoring. Numerous takeaways are applicable to both product manufacturers and implementing organisations as they collaborate.

Takeaways for the development of smart headband for fatigue risk-monitoring. Product manufacturers should:

- adopt a transparent and privacy-oriented algorithmic approach to build trust among the workforce;
- establish a step-by-step cooperation framework with the clients, emphasising efficient change management and communication;
- prioritise enhancing system robustness for effective operation in remote areas with challenging connectivity;
- embed robust data security measures within the system to address potential cyberattacks and ensure user data confidentiality;
- emphasise proactive safety features that predict and mitigate risks before incidents occur, demonstrating clear advantages over reactive technologies;
- embed diversity and inclusion principles into the development and design of a universally applicable algorithm, fostering business advantages for the system user, but avoid designing and using the algorithm for performance measurement;

- promote workers involvement and engagement in system's deployment in order to minimise the barriers and foster acceptance;
- provide build-in mechanisms to ensure that the systems is used only as intended; and
- acknowledge the significance of ensuring user comfort in the design of the wearable.

Takeaways for the safe and healthy implementation of the smart headband for fatigue risk-monitoring. Employers should:

- implement clear policies and practices to address privacy concerns related to data collection and use, ensuring compliance with regulations;
- engage workers and representatives to address their concerns on privacy and monitoring; and the continued use of it:
- emphasise the importance of proactive fatigue management in contributing to an improved safety culture in the long run;
- integrate the wearable system into the organisational culture and OSH management practices to foster acceptance and maximise impact; and
- highlight how the solution supports individual wellbeing, encouraging workers to take precautions for their own safety while reiterating that the employer maintains the overarching responsibility for OSH.
- Commit as part of the OSH management system, that the of the smart headband will be used only as intended i.e. to effectively promote OSH.

As demonstrated by clients' (employers') willingness to implement the solution for constant positive change, the combination of OSH and business impact is an important win-win.

List of abbreviations

AI	Artificial intelligence
AR	Augmented reality
EEG	Electroencephalography
GPS	Geographical Positioning System
IBAS	Institute of Breathing and Sleep
IoT	Internet of things
ML	Machine learning
MUARC	MONASH University Accident Research Centre
MURT	Multiple unprepared reaction time
MWT	Maintenance of Wakefulness Test
OSH	Occupational safety and health
VR	Virtual reality

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