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Wearable Sensors for Continuous, Real-Time Monitoring and Risk Assessment of Mine Workers Health and Safety

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ABSTRACT

Mine workers are continuously exposed to a host of non-fatal stressors and potentially fatal hazards: noise exposure, excessive vibration, poor air quality, toxicant exposure, ignition of combustible gases, equipment-related accidents, and thermal heat stress.

Wearable or portable sensors and contextual analytics provide a platform to unobtrusively collect and fuse multi-modal health and safety data in real time to compute both acute safety and longitudinal health insights. This paper presents preliminary trial results, conducted by Simtars, VigiLife, Inc., and Queensland Mines Rescue Service, of the application of wearable sensors to monitor heat stress and other vital biometrics for mines rescue personnel.

INTRODUCTION

In the challenging and often perilous environment of mining, the health and safety of mine workers are of paramount concern. Continuous exposure to a myriad of stressors, including overexertion, toxicant exposure, explosions, and thermal heat stress, poses significant risks to their well-being. These risks are exacerbated by the unpredictable mining conditions and varied techniques employed [1, 2]. The consequences of neglecting these risks not only threaten individual miners but also jeopardize the safety and productivity of the mining companies. Among these hazards, heat stress stands out as a particularly insidious threat, as it can lead to fatal outcomes even though it is entirely preventable. In addition, fatigue and chemical exposure are of particular concern in the mining environment. Yet, most organizations in the mining industry lack the technology and tools to predict and mitigate these health and safety risks effectively.

Health Hazards

High-temperature stress conditions can lead to elevated body temperatures among mine workers, thereby increasing the risk of heart-related ailments and potential fatalities [3]. Recent evidence demonstrates a substantial reduction in physical work capacity (i.e., as much as 35–76%) when workers are required to operate in environments with high temperatures and humidity [4]. Research conducted in an underground mine over a 12-month period in Australia reported 106 cases of heat exhaustion requiring medical intervention while similar studies in surface mine operations revealed a high prevalence of heat-related illnesses with 87% of surveyed miners displaying symptoms [5].

Responses to heat stress are governed by a combination of inter-individual factors, such as sex, age, and intra-individual factors encompassing fitness, medication usage, hydration status, shift duration, and illness, as shown in Figure 1.

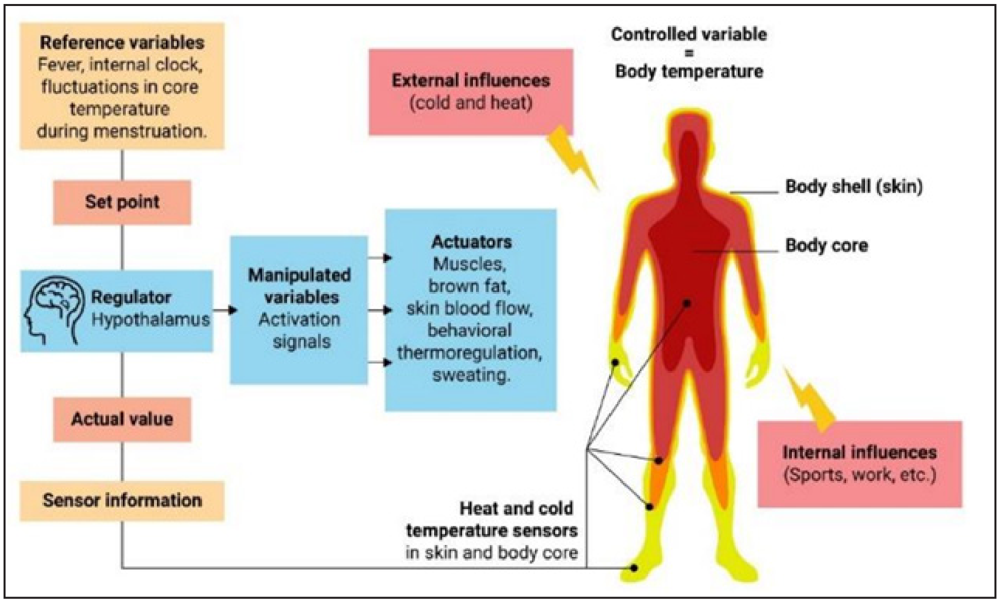


Figure 1. Control loop of thermoregulation with internal and external influences on body and TC [6]

Yet, Australia's Work Health and Safety laws lack a specified 'stop work' temperature, making it challenging to protect workers solely on an individual basis without considering their physiological responses [2]. According to [6, 7], there are inadequacies in the current safety measures, particularly with the use of the Wet-Bulb Globe Temperature (WBGT) as a heat stress indicator since the WBGT system underestimates the stress from restricted evaporation and through potential measurement errors. Generally, the "normal" body temperature falls within the range of 36.1°C to 37.2°C with temperatures exceeding 38°C typically indicating the presence of fever or illness [6, 7]. Furthermore, the human body is ill-equipped to endure significant fluctuations in core temperature [8]. Severe cases of hypothermia or hyperthermia can result in permanent organ damage or even fatality, underscoring the importance of continuous core temperature monitoring. In addition, current practices in the mining industry involve recording body temperature at three distinct time points, which may overlook temperature peaks in workers.

In the last few decades, several attempts have been made to non-invasively predict the core temperature (TC) using single or multiple physiological parameters, such as heart rate (HR), skin temperature, and heat flux [9, 10, 11, 12]. The Estimated Core Temperature algorithm (ECTemp™) was developed to estimate TC based on sequential HR observations alone using a Kalman filter [13] and a sigmoid curve [14]. ECTemp™ has been shown to provide an accurate indication of thermal strain in military personnel during moderate-intensity activities (i.e., road march) and endurance exercise (up to 24 h) in laboratory and field settings [9, 15].

Fatigue can be categorized into three distinct types: physical, mental, and emotional. Physical fatigue typically arises from prolonged muscle use, mental fatigue relates to the inability to maintain focus, and emotional fatigue, often referred to as chronic fatigue, results from prolonged exposure to constant stress [16]. While non-chronic fatigue necessitates subjective measurements or psychological and behavioral tests for assessment [17], chronic fatigue can be effectively monitored using HR variability [18].

Gas explosions and air pollution in mines are still common, posing increasing challenges [19]. Present security monitoring systems fall short in collectively tracking all environmental parameters adequately, including air pollution and chemical gas exposure, alongside miners' biometrics. Furthermore, due to the absence of clear boundaries between safe and hazardous workplace environments, relying solely on a gas sensor proves ineffective in the mining industry [20].

Health Hazards Monitoring

Prior attempts to collect data from working miners using goniometers and in-shoe pressure sensors faced difficulties, primarily due to harsh working conditions that often led to the failure of externally attached goniometers [21]. In recent years, companies like Cortex Design and Vandrico have introduced innovative smart safety helmets equipped with temperature and humidity sensors, as well as gas sensors capable of detecting methane, radiation, and carbon monoxide [22]. These helmets also incorporate brain activity sensors to gauge worker fatigue and issue alerts when hazardous gas concentrations exceed safe levels. However, some users expressed skepticism regarding the cost-efficiency and efficacy of technology that purports to measure brain activity with significant motion artifacts present. In situations of high risk, a sensor module integrating multiple sensors for real-time gas monitoring, coupled with continuous tracking of individual biometric health data, can offer precise insights to control stations regarding chemical exposure levels and their long-term implications. Therefore, emerging wearable technologies capable of collecting data on human performance and monitoring physiological parameters show potential for acquiring directly measured data that can provide valuable health and safety insights for mine workers [21]. Still, the current practice of health analysis remains periodic and relies heavily on voluntary participation [1]. Therefore, developing a data analytics framework that includes medical features and patterns of physiological health parameters for each individual miner is imperative to understanding the mining-related factors that may lead to long-term health complications [1].

Nevertheless, the scale of health monitoring solutions, considering the number of workers and the daily data collection required to prevent future health risks, generates a significantly large volume of data. To manage this data effectively, technology, such as artificial intelligence (AI), could be instrumental in analyzing vast datasets and identifying trends that help comprehend when and how these diseases occur. Consequently, wearable devices, continuously monitoring both environmental conditions and individuals' vital signs, hold the potential to contribute significantly to the early detection of diseases and the understanding of disease formation. An evaluation of the suitability of wearable health monitors for the mining industry in eight distinct areas related to heat stress, physical strain, respiratory health, fatigue, environmental conditions, ergonomics, incident monitoring, and long-term trends and patterns is summarized in Table 1. Wearable sensors could offer valuable support in the assessment of miners' health and safety by maintaining continuous monitoring of individual physiological indicators, thereby, reducing or eliminating the reliance on generic environmental assessments.

In this paper, preliminary trial results of the application of wearable sensors to monitor heat stress and other vital biometrics for mines rescue personnel are presented, confirming the feasibility of using wearable sensors and associated analytics for real-time monitoring of biometric data in extreme environmental conditions.

TESTING METHODOLOGY

Field trials of wearable sensors and associated applications were conducted by Simtars' Mine Safety at Queensland Mine Rescue Station (QMRS) in Dysart, Queensland, Australia, over 3 consecutive days. Both quantitative data, through sensor measurements and analytics, and qualitative data, via questionnaires, were collected during and after the trial, respectively.

Variables and Participants

The variables measured or estimated during the trial included HR, TC, motion, work intensity, humidity, wind speed, and air temperature. The ambient environmental conditions were measured using a combination of portable chemical sensors and internet-based weather sources.

A total of eight participants, ranging in age from 24 to 44 years old (average of 34) were included in the testing. Their typical workdays (outside of training as mine rescuers) ranged from office workers with only occasional forays into a hot mine to stope miners who spent 12-hour shifts in the heat.

Devices and Applications

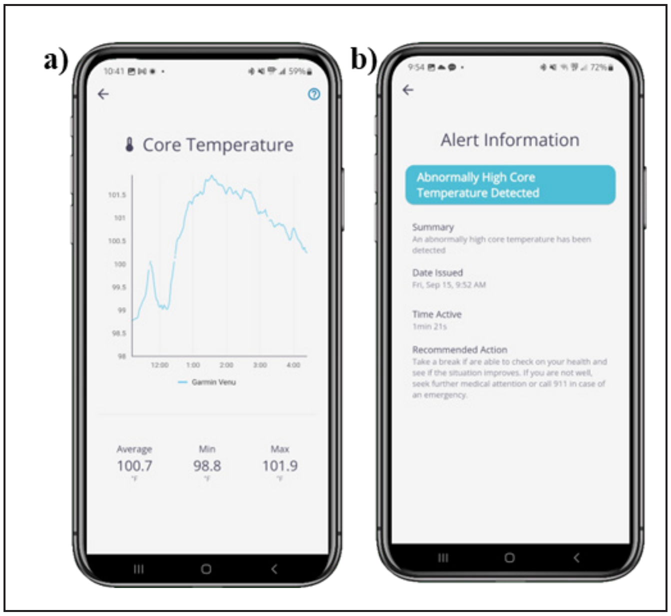
The participants were equipped with the Polar Verity Sense (PVS) sensor measuring the participants' HR and motion intensity and enabling real-time data collection and analysis using the SafeGuard Live mobile application (Figure 2a, 2b, 2c, 2d), which served as a central platform for data aggregation, management, and remote viewing. To monitor the environmental conditions during the study, the RKI GX-3R Pro portable monitor was used by the trainer for real-time detection and measurement of various gases including oxygen, flammable gases, carbon monoxide, and hydrogen sulfide, which can exist in underground spaces such as mines (Figure 2e).

The PVS streamed HR values at a rate of about 1hz to SafeGuard installed on a mobile device. SafeGuard's algorithm library then estimated TC and metabolic rate (Figure 3a). The PVS uses Bluetooth and ANT+ telemetry protocols and it has the capacity to stream to two Bluetooth devices without any limitations on the number of ANT+ devices [26]. All data was timestamped and stored on both the participants' mobile phones and within the SafeGuard cloud when internet connectivity was available. The GX-3R Pro streamed second-by-second data using Bluetooth protocols to SafeGuard for visualization and storage by both the participant and remote safety attendants. GoPro Cameras were utilized to visually document the participants' activities throughout the testing phases.

Table 1. Wearable health monitoring areas considerations for tahe mining industry

Types of Issues	Current State	Wearable Device Solution
Heat Stress	WBGT used solely as an indicator for heat stress is “deeply flawed” [5]	Continuously measures each individual TC depending on inter-individual and intra-individual factors [6].
Physical Strain	Wearable devices purporting to measure physical strain could benefit from additional validation [23].	Data can be anonymized and used by managers to plan breaks and monitor fluctuations in HR and TC [24].
Respiratory	Security monitoring systems cannot monitor all environmental and chemical exposure parameters collectively while considering a mine rescue’s individual biometrics [20].	Gas sensors, alongside weather and intra-individual factors, can be used to determine the amount of gas exposure.
Fatigue	Chronic and non–chronic fatigue is not monitored.	Chronic fatigue can be monitored by using the HR variability [18]. For non-chronic fatigue, a questionnaire can be used.
Environmental	Several different devices are required to monitor different health and safety measures, not environmentally friendly.	Several sensors are included in one device, which can be continuously re-used.
Ergonomics	The industry is starting to recognize the potential benefits of technology in enhancing worker safety and overall operational efficiency	Sensors integrated into helmets, uniforms, and straps. [25].
Incident	On average, nine mine workers die each year. Trips, falls, and slips made up for 25% of claims [1].	Can track live location and detect motion and send an alert to the monitoring team [19].
Long-Term Trends and Patterns	Health analysis is periodic in nature and heavily depends on voluntary participation [1].	Continuous monitoring of both the environment and individual is useful in the early detection of diseases and in understanding how diseases form [21].

Figure 2. Images representing the technologies used within the trial. a) SafeGuard Live web view, b) SafeGuard Live tablet view, SafeGuard Live, phone view, d) Polar Verity Sense heart rate monitor with armband, and e) RKI GX-3R Pro multi-gas chemical sensor



Abnormally High Core Temperature Detected

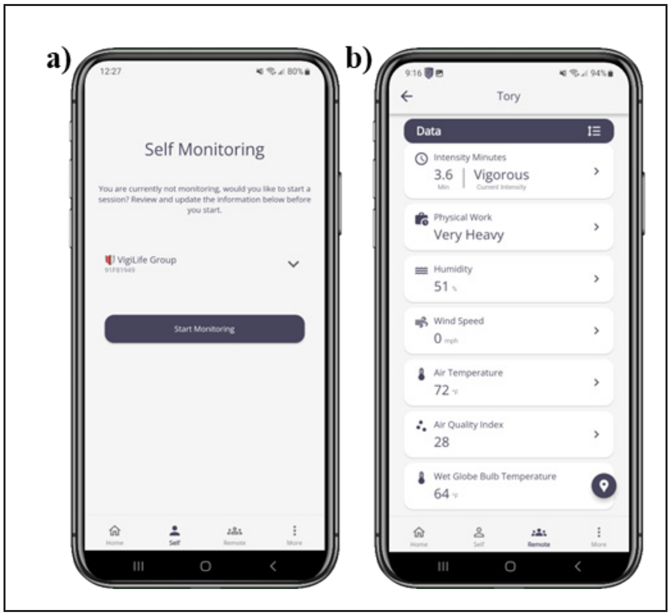
Summary
An abnormally high core temperature has been detected

Date Issued
Fri, Sep 15, 9:52 AM

Time Active
1min 21s

Recommended Action
Take a break if are able to check on your health and see if the situation improves. If you are not well, seek further medical attention or call 911 in case of an emergency.

Figure 3. **SafeGuard screenshots highlighting. a) TC, b) alert notification experience**



You are currently not monitoring, would you like to start a session? Review and update the information below before you start.

VigiLife Group
91F81949

Intensity Minutes: 3.6 Min | Vigorous Current Intensity
Physical Work: Very Heavy
Humidity: 51 %
Wind Speed: 0 mph
Air Temperature: 72 °F
Air Quality Index: 28
Wet Globe Bulb Temperature: 64 °F

Figure 4. SafeGuard screenshots showing. a) group selection and starting monitoring display, b) personal dashboard of user data

Safeguard Live application can establish connections with multiple wearable sensors and is capable of monitoring physiological metrics, location data, and environmental information [27]. When paired with compatible sensors, it provides participants with alarm function (Figure 3b), monitoring privacy through the opt-in session initiation feature (Figure 4a) and full access to their own data through the personal dashboard (Figure 4b).

enabling supervisors to effectively oversee the health and safety of users [27].

Before the testing, each participant was equipped with a PVS and a mobile gateway (a mobile phone). The SafeGuard application was installed on mobile phones followed by establishing a Bluetooth connection between the PVS and the application. Additionally, participants were required to input fundamental demographics, such as, height, age, and weight into the application to enable personalized analytics and accurate post-trial analysis. Two different types of tests were conducted:

1. **Baseline Test (Dysart)**—Test participants (mine rescuers) had their biometrics measured, monitored, and recorded during routine, low-activity behavior (Classroom activity).
2. **Concept Test (Dysart)—**Test participants had their biometrics data monitored and recorded while undertaking operational tasks: Long Duration Breathing Apparatus (LDBA) preparation and marching, container training, firefighting, and search & rescue.

Throughout the testing period, participants assumed four distinct roles on a rotational basis: Captain, Vice-Captain, Fresh Air Base, and Vice Fresh Air Base, in addition to undertaking specific training activities. The Captain and Vice-Captain roles were responsible for leading the team in various activities and ensuring the safety and efficiency of rescue operations in the event of emergencies or accidents during the training. Those assigned to the Fresh Air Base roles played a critical part in maintaining a secure and healthy environment for the trainees. Their contributions were directly linked to accident prevention, air quality maintenance, and the reduction of health risks. To protect personal privacy, the participants signed consent forms and a de-identification process was implemented by assigning each participant a unique number from 001 to 008. These assigned numbers remained constant throughout the entire testing period.

The participants were monitored during a series of activities (Figure 5). The activities included: classroom debriefings e.g., low-stress testing in the morning, Long Duration Breathing Apparatus (LDBA) preparation (Figure 5a), LDBA marching around the premises of the QRMS headquarters (Figure 5b), container training, where ventilation surveys occurred (Figure 5c-d), fresh air base (FAB) (Figure 5e), and three-story mazes (4 m × 10 m), where firefighting and search & rescue missions occurred and where wet room—hot and humid room configured to be at 44–47 degree Celsius and a humidity of 100%

Figure 5. Field trial activities. a) LDBA preparation, b) LDBA pack marching, c-d) container training, e) FAB, f) maze, hot and humid training, g) mine rescue, h) firefighting

was located (Figure 5f, 5g, 5h). The combustion container, within the 3-story maze (25 m × 7 m) had an average of around 90 to 100 degrees Celsius and a maximum of 140 degrees Celsius, where smartphones may have a high chance of being shut down. This is where firefighting exercises were undertaken.

After completion of the daily training, all recording devices were deactivated, and the collected data was explained to the participants. After the 3-day testing period

RESULTS AND DATA ANALYSIS

Quantitative Assessment

The correlation of measured HR and estimated TC to various mine rescue activities and job functions was examined to determine the feasibility of using HR as an indicator for the monitoring and prevention of heat stress and physiological strain (1). The ECTemp algorithm used sequential HR values and a Kalman filter to estimate TC, (29). Figure 6 shows the trial's participants' HR and estimated TC throughout the trial. Figure 6a shows the HR of the participants for the last day of the trial. Average baseline HR was 99.50 ± 21.49 BPM and rose to an average peak HR value of 159.12 ± 14.99 BPM. The range of HR was 92.88 ± 13.60 BPM. During the trial, TC changed gradually from an average baseline TC of 37.46 ± 0.45 °C to an average peak TC of 38.20 ± 0.44 °C (Figure 6b). The range of TC was 1.22 ± 0.41 °C.

Figure 7 further highlights the personal nature of TC and its alignment with various activities throughout the day. Generally, individuals' TC peaked between 13:30 and 14:30 hours. This specific timeframe coincides with the period during which participants were actively engaged in physically demanding activities i.e., firefighting or search & rescue within the maze in hot and humid conditions. The synchronized elevation in both HR and TC during this phase underscores the intricate connection between the cardiovascular system and the body's TC regulation mechanisms, offering valuable insights into the participants' physiological responses during these challenging conditions. Participants 006 and 007, who participated as trainees, vice-captain and FAB on that day: exhibited a rise and fall of the HR and TC, which meaningfully corresponds with their type of activity as well as their intensity of work. For instance, between 13:45 and 14:30, while Simtars 001 and Simtars 006 are resting after the firefighting activity, allowing their HR and TC to decrease, Simtars 007 starts cleaning the room, which elevates his HR and TC.

These findings are consistent with prior findings [28, 29, 30], which indicate that HR as a potential marker of heat stress, displays a similar pattern to TC, albeit with a slight time delay. The estimated TC data was compared with the established guidelines [31], which allowed an assessment of an individual's temperature concerning safe limits (Figure 7) and thus allowing a quick and clear evaluation of whether TC values were approaching a critical point, helping in the early detection of potential heat-related health risks.

Metabolic rate was estimated by SafeGuard using HR values measured by the PVS. Metabolic rate can provide useful insights in assuring that participants were not subjected to excessive physical strain, which can lead to fatigue, accidents, and injuries over extended periods. Figure 8 shows the data acquired for Simtars 001, who had an increase in metabolic rate during the firefighting activity. However, since a specific amount of time that universally

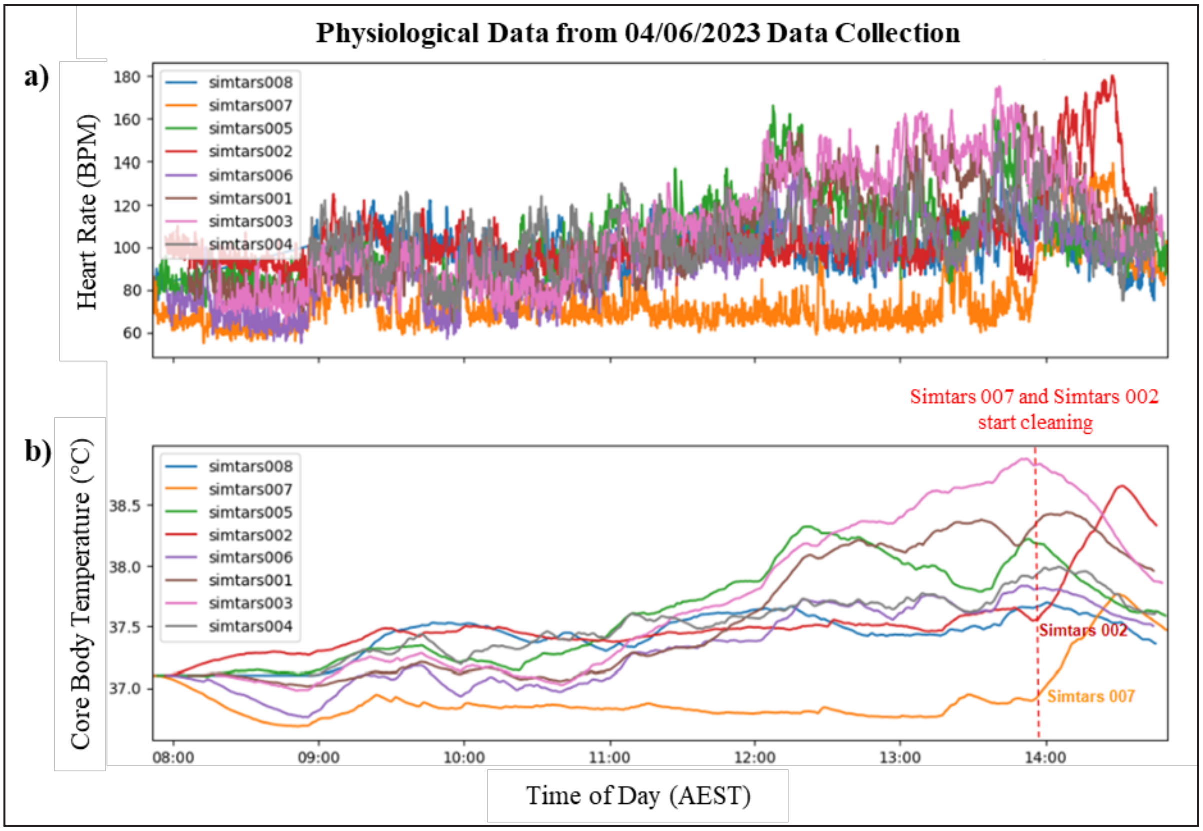


Figure 6. Representative physiological data collected on 04/06/2023 highlighting. a) HR and b) estimated TC for eight participants. Participants 002 and 007 initiated physically demanding cleaning activities

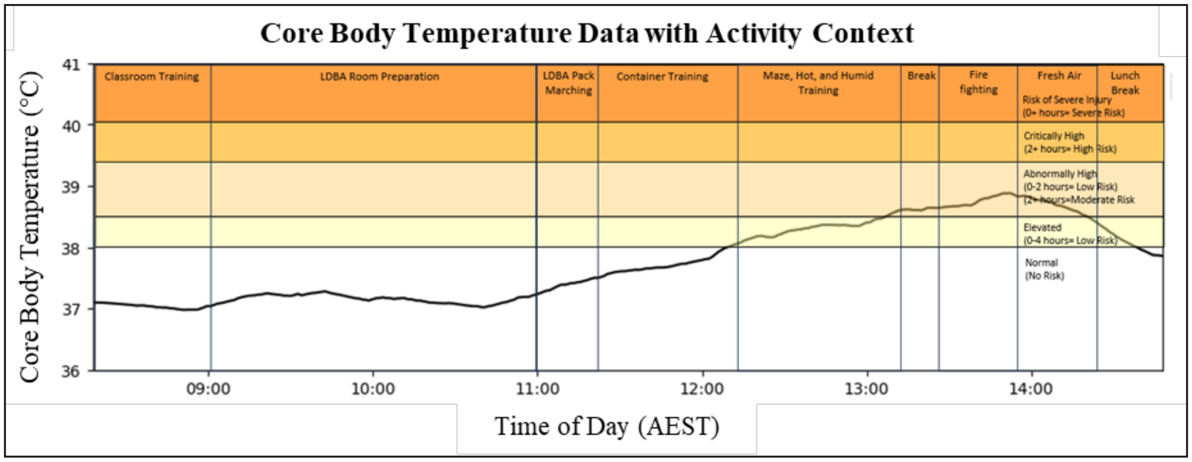


Figure 7. Representative data of TC and additional context for participant 003 operating in the Captain's role

defines when a high metabolic rate becomes problematic is not defined, therefore, when using the metabolic rate as an indicator of workload, a participant's age, overall health, and lifestyle style choices must also be considered alongside the HR and TC of the participant.

The data obtained from the gas detector, worn by the trainer, indicated that the sensor operated with real-time precision and accurately discerned the correct gases (Figure 9).

Low oxygen (O_2) levels and elevated carbon monoxide (CO) levels were detected outside of the normal concentration levels. Low concentrations of hydrogen sulfide (H2S), and ammonia (NH3) were detected, however, both chemical concentrations were within the safe limits with no

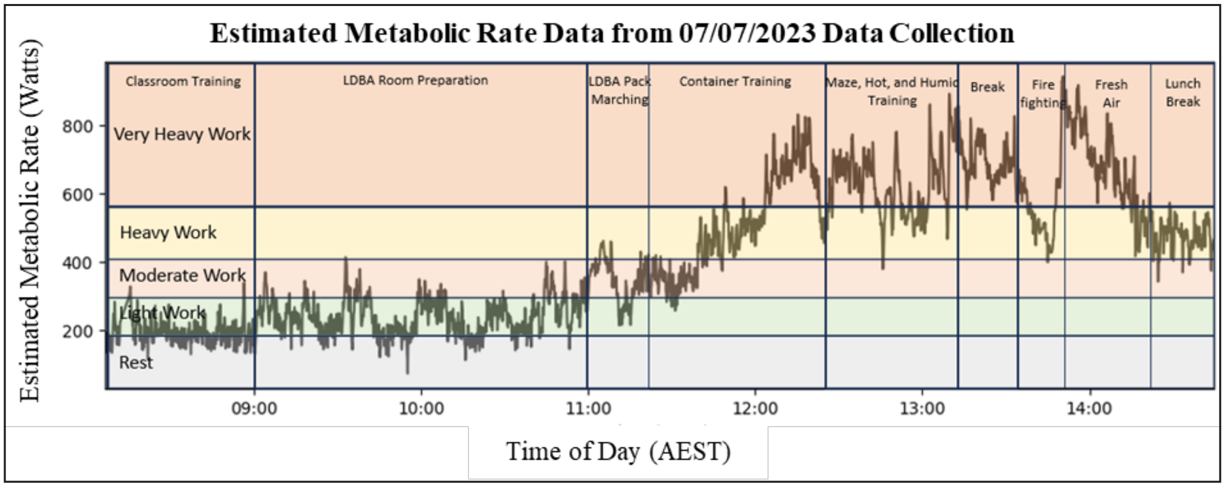


Figure 8. Representative data highlight the estimated metabolic rate and activity context for participant 001 operating as the trainee role

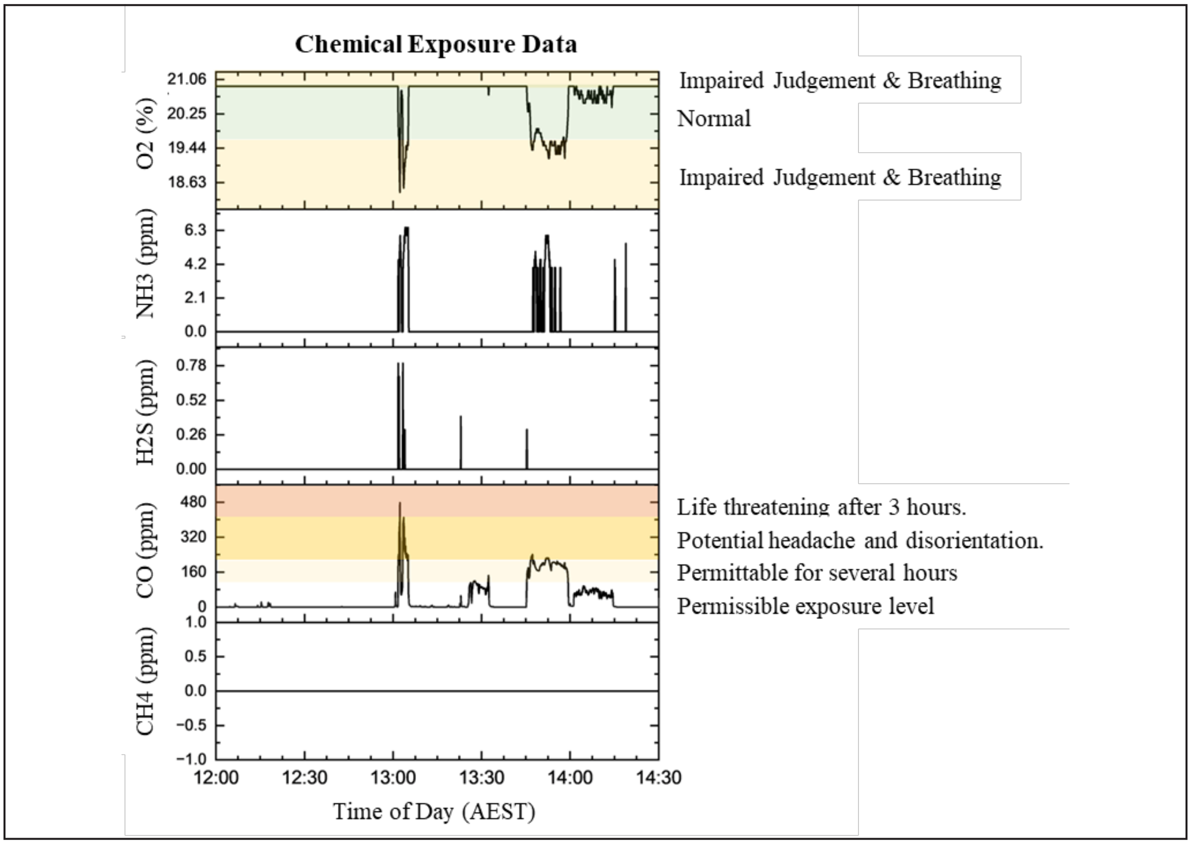


Figure 9. Representative chemical exposure data measured using the RKI GX-3R Pro technology (on the right of the graph - common characteristics experienced with various chemical exposure concentrations are described)

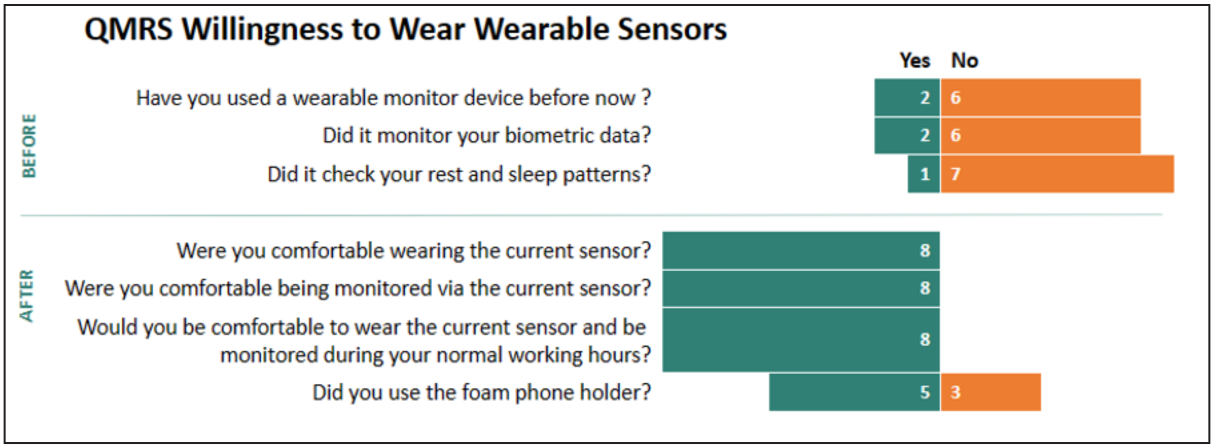


Figure 10. Summary of the user feedback collected using the pre- and post-trial survey

methane (CH4) present in the atmosphere, which was to be expected. It is important to note that individual tolerance to chemical exposure can vary, and certain people may be more sensitive to its effects. Prolonged or repeated exposure to chemicals at levels exceeding the recommended exposure limits can lead to respiratory irritation, eye irritation, coughing, and other long-term health issues.

Qualitative Assessment

The qualitative assessment was undertaken using a questionnaire that addressed the participant's overall experience with wearable health monitoring devices before and after the trial. As seen in Figure 10, while most participants had no prior experience with using a wearable sensor for health monitoring before the trial, they had a positive experience throughout the trial and found the technology valuable and comfortable enouagh to be willing to use it in the future.

CONCLUSIONS

In this study, the feasibility of using wearable technology to monitor the health and safety of workers in high-risk environments, such as underground mining, was investigated.

The main objectives of this effort were to demonstrate that wearable sensors can: (1) withstand durability and human factors requirements (e.g., high heat and comfort during extended wear), (2) provide real-time analytics and telemetry to produce valuable insights to workers and health and safety leaders alike when paired with a robust software platform, and (3) be viewed favorably by workers as a real-time safety monitoring solution. The trial results show that the wearable sensors can withstand extreme environmental conditions, the real-time analytics can provide real-time monitoring and alarms, and the use of wearable sensors was deemed acceptable by the participants.

Biometric data acquired from the study participants using the wearable sensors, their medical history and medication use, their daily habits (tobacco use, alcohol use, daily exercise, sleep regimen, TC), in addition to the data received from the chemical sensor, as well as information from local air channels, provided a holistic view of the situation in which workers are operating. This could potentially enable a health supervisor or manager to make the right decision at any moment for all individuals in the team. While the study would have benefited greatly from a simultaneous TC measured by a gold standard method, such as an ingestible telemetric temperature capsule system, due to limited resources, this was not possible. However, the results showed in this paper are the estimated TC from sequential HR using the ECTemp algorithm.

The qualitative data showed that while most participants had little to no experience with using wearable technology and a health monitoring mobile application as part of their daily work routine, they had a positive experience during the trial and were willing to wear wearable sensors as part of their daily work routines.

FUTURE DEVELOPMENTS

The small sample size of this initial effort limited the ability to make broad claims, however, the initial results regarding the use of wearable sensors and a real-time monitoring system for monitoring key safety parameters, such as estimated TC, ambient temperature and humidity, and noxious gases, were promising.

A larger sample population would be needed to confirm these promising initial results.

While physiological monitoring of individuals is a valuable tool for evaluating heat stress, it may not provide the real-time decision-making support essential for the physically demanding occupation to efficiently address heat-related hazards. The predictive abilities of the Predicted Heat Strain (PHS) model, outlined in ISO 7933 (2004) [32], have now enabled the development of tailored guidelines, triggered by localized thresholds. These guidelines can empower on-site supervisory personnel to handle heat-related risks promptly and knowledgeably in both construction and mining sites. Consequently, an ongoing endeavor at SafeGuard is to harness the full potential of the PHS model, capitalizing on its predictive capabilities for two key objectives: firstly, to facilitate managerial decisions regarding optimized work-rest schedules for paced work, and secondly, to empower workers to self-regulate during self-paced work.

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A Hydrodynamic Approach for Sizing and Selection of Hydrocyclone—Parametric Scaling and Process Optimization

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ABSTRACT

A hydrocyclone is a piece of equipment commonly used as a classifier in mill circuit operations. Traditionally, hydrocyclone performance is characterized by the classification efficiency parameter, such as cut size (d50c), sharpness of separation (α) and bypass (Rf). A plethora of endeavors have already been made to develop parametric models to determine hydrocyclone performance that correlate design and process variables. In contrast to those studies, we made an attempt to develop an approach to derive required design parameters purely from hydrodynamic principles that provides a platform to optimize the operation of a hydrocyclone for a given application. In this selection methodology, we calculated the differential pressure at the air core, as well as the tangential velocity at the boundary of the air core from the vortex principle in a confined geometry at different operating regimes. A series of experiments were conducted using Weir's Cavex® hydrocylone where process variables—such as solids concentration and feed flowrates—were experimentally studied to determine the key classification parameters. For the validation of the current approach we used the same process variables to derive design parameters and compared them with the existing design. The current approach can provide insights towards the selection of design parameters and can be useful for mining industry professionals to optimize different operating parameters of hydrocyclones to achieve the best performance.

INTRODUCTION

The hydrocyclone separator is a popular unit operating in industrial processing; it utilizes the incipient centrifugal forces in the rotating fluid domain to separate suspended particles. The solid- fluid mixture is introduced through the inlet at high pressure that generates a swirling motion inside the cyclone. Research towards understanding the inherent flow behaviours of the fluid and the particles inside the hydrocyclone have gained popularity amongst the numerical and experimental fluid mechanics communities [1–5].

However, industrial friendly mathematical models are yet to be developed based on the existing research. Since the physics of particle and fluid flow behaviour inside a hydrocyclone is still a complex aspect to realize, the empirical models are normally used for evaluation of its performance. Two frequently used models for predicting industrial hydrocyclone performance are Plitt's model

[6] and Nageswararao's model [7]. Moreover, as the models are empirical, the coefficients against each variable have to be determined experimentally when either the material to be processed or the basic design of hydrocyclone are changed even marginally. As this is impractical in many