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Deploying Smartwatch Technology to Measure and Mitigate Heat Stress Among Maritime Transportation Workers

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LIST OF ACRONYMS

ACGIH - American Conference of Governmental Industrial Hygienists

CDC - Centers for Disease Control and Prevention

ECG - Electrocardiogram

EDA - Electrodermal Activity

GPS - Global Positioning System

HRI - Heat-Related Illness

HRV - Heart Rate Variability

NIH - National Institutes of Health

NIOSH – National Institute of Occupational Safety and Health

NOAA - National Oceanic and Atmospheric Administration

OSHA - Occupational Safety and Health Administration

PPE - Personal Protective Equipment

PPG - Photoplethysmography

SVM - Support Vector Machine

WBT – Wet Bulb Temperature

WBGT - Wet Bulb Globe Temperature

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1. PROJECT DESCRIPTION

Maritime workers who perform strenuous outdoor activities represent some of the most vulnerable populations to heat stress. This occurs when the body's ability to regulate temperature and maintain homeostasis is compromised due to extreme heat exposure, leading to both physiological and psychological harm. The Occupational Safety and Health Administration (OSHA) has identified maritime workers as high-risk for heat-related illness (HRI), including heat exhaustion, heat cramps, and heat stroke, which can be fatal in severe cases (OSHA, 2023). These workers often perform labor-intensive tasks in hot and humid environments for prolonged periods, generating internal body heat through exertion (Yi & Chan, 2017). Combined with sustained exposure to external heat, this can elevate the risk of HRI and lead to long-term physiological impairment. Heat stress may also reduce productivity, increase workplace accidents, and lower morale, underscoring its impact on both individual well-being and overall job performance (Chan, et al., 2012). The risk is further amplified by the urban heat island effect, where densely built environments retain more heat than rural areas (Lundgren et al., n.d.).

Excessive heat exposure forces the cardiovascular and nervous systems to work harder, especially when environmental temperatures exceed the normal human body temperature of approximately 37°C. To maintain thermal balance and sustain vital functions, the body must expend additional energy, increasing the physiological burden (Crandall et al., 2008; Low et al., 2011; Rowell, 1974). If left unaddressed, this burden can lead to serious health complications, including HRI.

Heat stress disproportionately affects vulnerable communities, and certain individual factors significantly increase the risk of contracting a heat-related illness. According to the U.S. Centers for Disease Control and Prevention (CDC), individual variables that raise the risk of experiencing HRI include high humidity, obesity, fever, dehydration, prescription medication use, heart disease, mental illness, poor circulation, sunburn, and alcohol consumption (Assistant Secretary for Health, n.d.). Individual risk factors are especially important to consider for maritime workers because the physically demanding nature of their jobs can exacerbate underlying health conditions. Additionally, long work hours, limited access to shade, and insufficient breaks can further compound these vulnerabilities.

With global warming trends, outdoor working conditions are intensifying, making it imperative to conduct research and investigate heat stress mitigation strategies that adequately safeguard worker well-being and safety. According to a recent study published by the National Oceanic and Atmospheric Administration (NOAA), calendar year 2023 was recorded as the warmest in history, with global average surface temperatures 1.18°C (2.12°F) above those measured in 1850, prior to the industrial era (NOAA, 2023). As global temperatures continue to increase, the number of days of human exposure to heat indices in the U.S., a combination of relative humidity and temperature, reaching 37.8°C (100°F) and 40.6°C (105°F) is predicted to double and triple, respectively, by mid-century when compared to a 1971-to-2000 baseline (Dahl et al., 2019). The strain on public health resources will only escalate as these extreme heat events become more frequent and severe.

Despite the well-documented risks of occupational heat exposure and the existence of environmental threshold-based guidance, current heat stress mitigation practices in maritime transportation largely rely on generalized environmental indicators and population-level recommendations. These approaches do not adequately account for individual physiological variability, task-specific exertion, or real-time changes in environmental conditions. As a result, existing protocols are often reactive rather than preventive and lack the capacity to deliver individualized, real-time warnings before heat-related illnesses develop. This gap highlights the need for scalable, wearable-based solutions that integrate physiological monitoring with environmental data to enable personalized heat-stress detection and timely intervention in maritime work environments.

If early warning indicators of heat stress can be identified, then detrimental physiological and psychological outcomes can be avoided. Continuous monitoring of at-risk individuals in high-heat environments is therefore essential, as it enables the implementation of heat stress prevention strategies in real-time to help reduce severe health outcomes, lower fatalities, and maintain productivity.

Wearable technology, particularly smartwatches, offers the potential to serve as a mechanism for identifying these indicators through real-time monitoring capabilities. A recent study by Sim et al. (2016) demonstrated that the skin temperature of an individual's wrist can predict whole-body thermal sensations.

The study undertaken and reported herein is guided by several research questions focused on exploring the potential for smartwatches to monitor and mitigate heat stress among maritime workers. First, it seeks to identify the key indicators used to quantify heat stress, critical for accurately assessing individual risk levels. Second, it explores whether smartwatches can be effectively utilized to measure heat stress in individuals engaged in prolonged outdoor activities. Lastly, we examine the potential for heat stress predictive models that incorporate a closed feedback loop to prevent heat-related illnesses.

Collectively, this exploration aims to provide a comprehensive understanding of how heat stress can be better monitored and managed in occupational settings. It lays the groundwork for developing practical applications for achieving timely and cost-effective heat stress detection and mitigation.

1.1 Objective and Scope

This phase of the research focused on establishing the scientific, technical, and operational feasibility of deploying smartwatch-based heat stress monitoring systems, with the following objectives:

- Identify and validate physiological and environmental indicators of heat stress relevant to an individual’s work environment.
- Evaluate the capability of commercially available smartwatch technology to measure these indicators in work environment settings
- Assess predictive modeling approaches capable of estimating heat stress risk in real time using integrated physiological and environmental data
- Develop a conceptual closed-loop feedback framework for early heat stress detection and intervention.

Note that this phase did not include large scale operational deployment or field trials. Rather, it emphasized research, feasibility assessment and conceptual system design to inform subsequent implementation and validation efforts in future research endeavors.

2. METHODOLOGICAL APPROACH

A structured search methodology was performed to identify relevant literature on heat stress monitoring and mitigation strategies. The process began by analyzing heat stress and its physiological mechanisms using peer-reviewed medical databases, including PubMed, Web of Science, and the National Institutes of Health (NIH). Studies that primarily focused on physiological responses to heat stress, also referred to as heat strain, were prioritized to help determine key indicators of heat stress.

Additionally, environmental factors that exacerbate heat stress and the current guidelines governing occupational heat exposure risks were considered. The review further explored continuous heat stress monitoring solutions through the lens of wearable technology, particularly smartwatches. It also investigated heat stress prevention techniques using predictive modeling, where physiological data from monitoring tools, such as smartwatches, were used to estimate core body temperature, a primary indicator of heat stress.

Studies were prioritized based on the following criteria: 1) a sample size of at least 30 participants to ensure statistical significance, 2) continuous monitoring of physiological parameters, particularly heart rate, heart rate variability, skin temperature, and electrodermal activity, and 3) real-world applicability, with a focus on experiments conducted in occupational outdoor settings. Furthermore, studies were examined based on their publication source, methodological rigor, and data reliability. This review synthesizes key findings across these sources to evaluate the potential of smartwatches as real-time heat stress monitoring tools and to highlight research gaps that can inform future advancements in occupational heat stress prevention.

3. RESULT/FINDINGS

3.1 Heat Stress Definition and Its Mechanism

Heat stress is defined by OSHA as the net heat load imposed on the body by external and internal factors, including environmental conditions, physical exertion, and clothing, all of which contribute to heat accumulation (Liljegren, 2008). This accumulated heat further adds to the body's net heat load, which also includes internal heat generated by metabolic processes. Metabolic heat is produced during physical activity and, even at rest, the body generates heat through basal metabolic processes such as breathing, digestion, and circulation.

While heat stress refers to the external and internal heat load imposed on the body, heat strain refers to the body's physiological response to heat stress (ISO, 2004; NIOSH, 2016). To manage increased heat load, the body activates various mechanisms to dissipate heat, including sweating, increasing heart rate, and vasodilation, the widening of blood vessels near the skin's surface to enhance blood flow and release heat. As the body undergoes heat strain, its core temperature rises. A normal core body temperature ranges from 36.1°C (97°F) to 37.2°C (99°F) (Yousef et al., 2024). If the body is unable to regulate the increased heat load effectively, and core temperature continues to climb, the risk of heat-related illnesses grows. Heat-related illnesses include a spectrum of conditions such as heat stroke, heat exhaustion, heat cramps, heat syncope, heat rash, and rhabdomyolysis, a rare condition that causes muscle disintegration due to injury or high levels of exercise without rest (Liljegren, 2008).

3.1.1 Health Impacts of Heat Stress

Each HRI is a serious consequence of the body's inability to regulate a high core temperature, which can become life-threatening. Heat stroke is the most dangerous HRI, and according to OSHA, it should be treated as a medical emergency. This condition occurs when the body's core temperature exceeds 40°C (104°F) within a 10-to-15 minute interval and can lead to impaired mental processes, such as the inability to think clearly or perceive dangerous situations (OSHA, 2023). Other symptoms of heat stroke include slurred speech, confusion, clumsiness, fainting or unconsciousness, hot dry skin, excessive sweating, seizures, and, in worst-case scenarios, death caused by organ failure (Liljegren, 2008, OSHA, 2023).

Continued exposure to high-temperature conditions can also be detrimental to long-term health. Extreme heat not only exacerbates chronic diseases, particularly cardiovascular issues such as heart failure and myocardial infarction, but also poses serious risks to respiratory health, potentially leading to respiratory alkalosis and tissue damage (Li, 2024; Wang et al., 2019). Additionally, heat exposure can be dangerous for pregnant women and infants, as it can increase the risk of preterm birth and cause complications such as fetal heart rate tachycardia and uterine contractions (Li, 2024; Saigal and Doyle, 2008). The potential for permanent organ damage, particularly to the central nervous system following heat stroke, further underscores the critical need to mitigate the effects of extreme heat on vulnerable populations.

3.1.2 The Vulnerabilities of Outdoor Workers to Heat Stress

Outdoor workers are particularly vulnerable to heat stress due to the nature of their work, which often involves prolonged physical activity in high-heat environments. Work sites frequently lack adequate shade, leaving workers with limited opportunities to cool down (OSHA, 2023). The inherent risks are further exacerbated by activities that typically involve exposure to direct sunlight, significantly increasing the net heat load (Yi and Chan, 2017). Additionally, the physically demanding nature of many tasks generates extra metabolic heat. Moreover, the thickness and weight of the clothing worn, particularly personal protective equipment (PPE) like impermeable coveralls, contribute to rising core body temperatures by trapping heat and limiting the body's ability to cool down (OSHA, 2023). Furthermore, accumulated worker fatigue due to high ambient temperatures can lead to a significant decrease in task performance and an increase in onsite work accidents, as demonstrated by a greater decline in performance and more accidents during the summer months compared to winter (Bendak et al., 2022).

As global warming increases, outdoor workers will face higher temperatures for extended periods. During the summer months, workers may be frequently exposed to temperatures exceeding 32°C (90°F) for several hours each day. In some high-heat regions in the U.S., they can face temperatures of over 38°C (100°F) for more than 100 consecutive days annually, significantly raising the risk of heat-related illnesses (OSHA, 2023). This trend exemplifies the growing threat that global warming poses to outdoor workers. Other external factors related to social, economic, and environmental disparities can significantly increase the vulnerability of maritime workers to heat stress.

3.2 Heat Stress Mitigation in Maritime Shipbuilding

Maritime workers engaged in shipbuilding activities face significant heat stress risks due to harsh working environments, exposure to high-temperature sources, and physically demanding tasks. The shipbuilding process involves multiple high-heat operations, including steel cutting, welding, sandblasting, and painting, which require prolonged exposure to confined or poorly ventilated spaces (Rose, 2017). For instance, when assembling and welding large blocks within shipbuilding halls, most workers experience high temperatures, which are exacerbated by heat from welding equipment and other machinery (German Naval Yards, n.d.). In addition, the confined spaces of shipbuilding halls restrict airflow, which limits heat dissipation. When combined with poor ventilation, this leads to an increase in the body’s net heat load, raising the risk of contracting a heat-related illness. Furthermore, the risk of heat stress increases during the summer months or in warmer climates.

Within these settings, heat stress mitigation is crucial due to the nature of the tasks performed. The typical work procedure involves heavy lifting, lengthy periods of standing, and manual handling of hot materials. As a result, each of these activities can increase body heat. Workers performing sandblasting and painting face unique heat hazards, as tasks are generally performed within enclosed environments or sheds that are temperature and humidity controlled, but the physical exertion required can increase the risk of heat exhaustion (Zanelli, n.d.). Additionally, the outfitting stage, which primarily involves installation of machinery and other components within the vessel, occurs in poorly ventilated and confined areas where heat quickly accumulates, exacerbating the conditions for heat stress.

Heat stress reduction in the maritime industry extends beyond worker thermal comfort, as it is essential for their safety as well. Exposure to severe temperatures, coupled with inadequate heat stress management, may also reduce worker productivity, increase error rates, and raise accident risk. For example, during the dock assembly stage, heat-related fatigue or cognitive impairment can lead to dangerous mistakes such as the improper assembly of large blocks or faulty welds. In turn, a vessel’s structural integrity can potentially be compromised. Research has shown that heat stress has a detrimental effect on cognitive performance, resulting in a decrease in attention span, memory retention, and reaction times (Hancock and Vasmatzidis, 2003). These factors can significantly increase human error in high-accuracy tasks, such as welding and assembly.

In accordance with the National Institute for Occupational Safety, mitigating heat stress with proper hydration, cooling stations, and scheduled breaks are critical protective measures for workers exposed to elevated temperatures (NIOSH, 2016). For maritime workers, these protocols are especially crucial during high-exertion activities such as welding, sandblasting, and assembly. Furthermore, wearable technology that can continually monitor physiological indicators such as heart rate, heart rate variability, skin temperature, and perspiration rate may enable the early detection of heat stress in real time. When integrated with data-driven predictive modelling, heat stress risks can be estimated by combining physiological data collected from wearable technology with environmental factors such as temperature, humidity, wind speed, and solar radiation. Identifying heat stress trends and patterns in real time allows supervisors to take prompt action to prevent the escalation of heat stress, ensuring worker safety and health while maintaining operational efficiency.

3.3 Physiological Indicators of Heat Stress

Numerous studies have demonstrated a correlation between physiological responses and thermal comfort (Kim et al., 2018; Mansi et al., 2021; Nazarian et al., 2021). The following discussion explores the methodologies for measuring these physiological responses using wearable sensors. Additionally, it describes the limitations of these experimental approaches and highlights opportunities for enhancing these methods.

3.3.1 Heart Rate, Heart Rate Variability, and Photoplethysmography

Various research investigations have utilized heart rate measurements to predict individual heat stress, as heart rate is one of the earliest indicators of physiological strain (Liu & Wang, 2017). However, although heart rate functions as an early sign of heat stress, it lacks specificity due to its sensitivity to hydration levels, fatigue, and psychological stress (Yao et al., 2018). Studies have consistently shown that individuals working in hot environments experience an increase in heart rate (Mansi et al., 2021). According to the American Conference of Governmental Industrial Hygienists (ACGIH), heat stress is characterized by the occurrence of one or more of the following conditions: 1) after one minute of recovery, heart rate surpasses 120 beats per minute (bpm) following intense physical exertion, 2) heart rate remains above 180 bpm minus the individual's age in years for a prolonged period, 3) individuals who are not acclimatized to the environment experience a core body temperature exceeding 38°C (100.4°F) or medically selected acclimatized individuals experience a core body temperature over 38.5°C (101.3°F), or 4) individuals exhibit heat-related symptoms such as vertigo, dizziness, fatigue, or fainting. In their study, Ruas et al. (2020) assessed the relationship between heart rate and body temperature in heat-exposed workers, as heart rate has been recommended by the ACGIH as a potential measure of heat stress. The study utilized a non-invasive wearable heart rate monitor that enabled individuals to quantify their heart rates.

Heart rate variability (HRV), defined as the variation in time intervals between consecutive heartbeats, has the potential to be another useful indicator of heat stress (Shaffer and Ginsberg, 2017; Yamamoto et al., 2007). HRV is modulated by the activity of the parasympathetic and sympathetic branches of the autonomic nervous system (Mansi et al., 2021). Researchers from Yamaguchi University demonstrated that human exposure to a Wet Bulb Globe Temperature (WBGT) of 35°C (95°F) led to the activation of the sympathetic nervous system and the simultaneous suppression of the parasympathetic nervous system (Yamamoto et al., 2007). The electrocardiogram (ECG), also referred to as EKG, is frequently employed in several related investigations for the purpose of assessing HRV. However, while HRV provides more information on autonomic nervous system function, its reliability declines with physical activity because movement artifacts can interfere with readings (Shaffer and Ginsberg, 2017). To record electrical activity of the heart using ECG, electrodes are affixed to an individual's arms, legs, and torso, which necessitates a more intricate procedure. ECG has the potential to indicate thermal comfort levels due to the autonomic nervous system's regulation of heart rate and the cardiac cycle (Mansi et al., 2021). Heat stress induces a shift in the sympathovagal balance of the autonomic nervous system, resulting in a predominance of sympathetic activity, which leads to an increase in heart rate and a reduction in HRV (Kontaxis et al., 2019).

Photoplethysmography (PPG), a technique used in smartwatches and other wearables, offers a less invasive alternative for monitoring heart-related metrics and shows promise as a method for assessing thermal comfort. PPG is an optical technique that employs low-intensity infrared radiation to assess alterations in blood volume within the peripheral circulation (Allen, 2007). This approach can also be used as an indirect assessment of heart activity. PPG signal analysis enables the computation of physiological responses that are highly related to acute hot weather, including heart rate, heart rate variability (HRV), inter-beat intervals, and heart rate reserve (Parsons, n.d.). In an experimental investigation that utilized physiological signal response datasets to train predictive machine learning models, it was found that PPG signals exhibited a lower degree of predictive capability in comparison to other physiological signals assessing heat strain during physical activities. The researchers involved in the study hypothesized that the correlation between physical activity and acute weather conditions, which can result in increased blood flow in the circulatory system, could diminish the predictive power of the PPG signal (Shakerian et al., 2021).

3.3.2 Skin Temperature

While heart rate is a useful indicator, relying solely on it to detect heat stress may not yield the most accurate results. This is because heart rate can be influenced by factors such as gender, age, fatigue, physical intensity, nature of the task, and anxiety. Therefore, a more comprehensive approach incorporating multiple physiological response measurements is recommended for a more precise assessment of heat stress (Yao et al., 2018; Yi et al., 2016). Skin temperature, for instance, is considered a reliable indicator of thermal comfort due to its role in thermoregulation processes. Studies have shown a correlation between fluctuations in peripheral skin temperature and an individual's perception of thermal comfort (Mansi et al., 2021).

A study conducted by researchers from Pennsylvania State University examined the impact of thermal climatic conditions on various physiological parameters such as skin temperature, heart rate, and blood pressure (Shakerian et al., 2021). The results revealed a statistically significant correlation between environmental heat stress and increased skin temperature, with individuals who sustained skin temperatures above 35°C exhibiting an increase in core body temperature. Moreover, even well-acclimated individuals can face fatal consequences when skin temperatures exceed 37 to 38°C (98.6 to 100.4°F), as core body temperatures can reach critical thresholds of 42 to 43°C (107.6 to 109.4°F) (Sherwood and Huber, n.d.).

3.3.3 Electrodermal Activity

An additional metric for assessing thermal comfort could be electrodermal activity (EDA), given the findings of multiple studies that perspiration is associated with thermal comfort (Mansi et al., 2021; Shakerian et al., 2021). Sometimes referred to as galvanic skin response or skin conductance, EDA refers to the skin's conductivity variance in response to sweat secretion, which typically occurs in small quantities (Mccleary, 1950). Sweat gland activity changes serve as an indicator of an individual's emotional state intensity, commonly known as emotional arousal or stress level. By applying a constant low voltage to two contact points on the skin using EDA sensors, it is possible to measure subtle differences in the electrical resistance of the skin.

However, because EDA measures sweat-induced conductivity changes, individual variations in sweat gland activity may reduce its reliability as a universal indicator (Giannakakis et al., 2022). EDA is advantageous for measuring sympathetic neural activity, as only the sympathetic nervous system stimulates perspiration glands (Ahn et al., 2019; Kappeler-Setz et al., 2013; Poh et al., 2010). An individual's phasic EDA increases in response to stress or demanding circumstances (Giannakakis et al., 2022). Widely utilized as a metric for determining the state of the autonomic nervous system, EDA can also be used to assess perceived risk, as perceived risk activates the sympathetic nervous system (Herrero-Fernández, 2016).

3.3.4 Environmental Indicators of Heat Stress

While mitigating heat strain through monitoring the body's physiological response is critical, it is also essential to understand the environmental conditions that contribute to an increase in the body's net heat load, thereby causing heat stress. Without accounting for external environmental factors such as ambient temperature, humidity, heat index, solar radiation, wind speed, and urban heat island effect, physiological monitoring alone may not fully capture the extent of heat-related risks. Gaining a comprehensive understanding of the environmental drivers of heat stress, in conjunction with corresponding physiological responses, is instrumental in preventing heat-related illnesses.

Wet Bulb Globe Temperature (WBGT) is a measure of heat stress on the human body in direct sunlight. According to the U.S. National Weather Service, this metric combines measurements from key environmental heat indicators such as temperature, wind speed, relative humidity, sun angle, and solar radiation, including cloud cover, to accurately detect heat stress (National Weather Service, 2021). WBGT uses three types of thermometers to collectively measure heat stress. The first is a wet bulb thermometer, which simulates how the human body cools itself through sweating. A wet cloth covers the thermometer, and as water evaporates under sun exposure, the thermometer cools. The second is a black globe thermometer, which measures solar radiation by capturing warming in direct sunlight and cooling when wind blows across it. The third is a dry bulb thermometer, which measures ambient air temperature in a shaded area (National Weather Service, 2021). The combination of all three thermometers provides a comprehensive assessment of heat stress.

WBGT offers a more accurate representation of heat stress compared to other methods, such as the heat index. The heat index, often shown in weather apps as the "real feel" temperature, estimates what the ambient temperature feels like to the human body based on relative humidity and air temperature (Perry, 2024). However, because it is measured only in shaded areas, it fails to capture the environmental conditions many outdoor workers face. For a more accurate assessment of personal heat stress, environmental factors such as wind speed and solar radiation must be considered, as they significantly affect physiological responses to extreme heat (Davis et al., 2024). The wet-bulb temperature (WBT), another commonly used measure, also falls short because it relies on a single wet-bulb thermometer to determine the lowest temperature air can reach through evaporation from a wet cloth (Perry, 2024). This makes WBGT a critical tool in understanding how environmental factors contribute to heat stress in humans. Due to its comprehensive nature, WBGT is used by organizations such as the U.S. Army and OSHA to develop guidelines for mitigating heat stress among workers in high-temperature outdoor environments (Davis et al., 2024; Liljegren, 2008; Sawka et al., 2003). Additionally, the International Standards Organization (ISO) has approved WBGT as a standard measure for assessing heat stress in humans (Brimicombe et al., 2023).

Guidelines from Heat Stress Threshold Limit Value documentation published by the American Conference of Governmental Industrial Hygienists (ACGIH) outline WBGT thresholds indicating when individuals are at risk. For moderate work levels, heat stress is considered high when WBGT values reach 30°C (86°F) for acclimatized workers and 27.5°C (81.5°F) for unacclimatized workers (American Conference of Governmental Industrial Hygienists, 202. As physical activity intensifies, these threshold limits are adjusted downward to account for the increased net heat load on the body. When WBGT exceeds 33°C (91.4°F), evaporative cooling through sweating becomes severely restricted (Jacklitsch et al., 2016). Additionally, heat stress can occur at lower temperatures if humidity is high. For instance, a dry temperature of 23°C (73.4°F) combined with high humidity can produce a heat index capable of causing heat stress among workers (Taylor et al., 2008).

Although WBGT thresholds are vital for detecting heat stress, they do not fully capture individual differences in heat stress susceptibility, such as variations in physical exertion, clothing characteristics, and personal health status. Consequently, reliance on environmental thresholds alone limits the accuracy of individual heat stress risk assessment. Most existing occupational heat stress frameworks continue to treat workers as a homogeneous population, reducing their effectiveness in environments characterized by wide variability in exertion, clothing, and individual physiology. Addressing this gap requires personalized monitoring approaches that dynamically integrate physiological responses with environmental conditions. A comprehensive assessment of heat stress is therefore essential for developing personalized predictive models and real-time alert systems capable of enhancing worker safety as global temperatures continue to rise.

3.4 Utilizing Wearable Technology to Monitor Heat Stress

Wearable technology has emerged as a powerful mechanism for health monitoring due to its ability to track physiological signals. These devices are used in a wide range of scenarios, including detecting health abnormalities, monitoring the body's response to physical exertion, assessing environmental impacts, and identifying spikes in biometric data that can signal early stages of disease (Kang and Exworthy, 2022). They can also collect and transmit real-time health data, which is crucial for preventing the onset of heat-related illnesses and enabling timely interventions (Jerath et al., 2023; Kim et al., 2018; Liu et al., 2019; Saheb et al., 2022).

Several types of wearable technology are currently used for health monitoring, including fitness trackers, smartwatches, and specialized medical devices. Smartwatches have gained popularity in health monitoring because they combine fitness tracking with advanced medical capabilities without being physically obtrusive. With their diverse sensing technologies, including accelerometers, skin temperature sensors, electrodermal activity sensors, and heart rate monitors, smartwatches provide an opportunity to effectively assess an individual's physiological state across varying environments (Jerath et al., 2023; Nazarian et al., 2021; Saheb et al., 2022).

3.4.1 Heat Stress Monitoring and Detection Using Smartwatches

Due to their ability to collect vital data on physiological parameters, smartwatches are highly relevant to heat stress monitoring. These devices integrate multiple sensors that allow for the real-time assessment of health-related risks. In addition, smartwatches can alert users when a physiological threshold indicative of heat stress has been crossed, enabling timely intervention (Saheb et al., 2022). For example, if a smartwatch detects a sign of heat stress, such as an elevated heart rate or rising skin temperature, the real-time feedback mechanism, tailored to the individual’s specific health profile, can prompt immediate actions, such as notifying the user or a healthcare provider. Studies conducted by Kim et al. (2018) and Liu et al. (2019) highlight the importance of developing personalized heat stress models and emphasize the critical role of wearable technology in health monitoring. For workers in high-heat environments, smartwatches serve as a vital early warning system. Their continuous monitoring capabilities can detect early physiological signs of heat strain, enabling intervention before the condition escalates into a life-threatening heat-related illness.

Commercial smartwatches, such as Google Pixel 2, Garmin Venu 2, and Fitbit Sense 2, feature cloud-based connectivity that allows for real-time physiological data transmission. This functionality is essential in occupational settings, as it enables continuous monitoring by both workers and supervisors. Immediate alerts can prompt individuals to take preventive measures, while remote surveillance allows safety personnel to respond when workers exhibit indicators of heat strain. Furthermore, analyzing long-term trends can enhance predictive heat stress models by tailoring them to individual risk profiles.

Smartwatch connectivity features also support integrated feedback mechanisms, enabling users to receive personalized health recommendations and real-time notifications based on collected physiological data (Jerath et al., 2023; Saheb et al., 2022). In a study by Mind Body Technologies, researchers used commercially available smartwatches to monitor psychological stress in real time by measuring heart rate, heart rate variability, and electrodermal activity (Jerath et al., 2023). When abnormal deviations were detected, users received visual notifications on their smartwatch prompting immediate behavioral adjustments, such as practicing relaxation techniques. This created a feedback loop that enabled personalized stress management interventions, supported by connectivity to smartphones and cloud platforms.

In addition to its feedback and connectivity features, smartwatches show potential for real-time monitoring of heat stress and thermal comfort, particularly in urban and occupational settings where heat exposure is intense. Project Coolbit introduced a novel wearable weather station using wrist-mounted devices that continuously tracked environmental parameters, such as air temperature and humidity, physiological responses including heart rate and skin temperature, and subjective feedback on thermal comfort (Nazarian et al., 2021). The study demonstrated that wrist-mounted sensors could accurately predict core body temperature non-invasively, offering a personalized assessment of heat exposure. This approach proved particularly effective in urban environments and provided actionable insights into thermal comfort and activity levels. The real-time data enabled a comprehensive evaluation of personal heat exposure, which can be critical for developing targeted interventions in high-risk environments.

Despite their promise, commercial smartwatches have limitations that can affect the accuracy and reliability of physiological data. While smartwatches are effective at monitoring parameters such as heart rate and user activity levels, external factors like excessive movement, improper fit, or environmental interference can compromise performance (Falter et al., 2022; Sarhaddi et al., 2022). For example, PPG signals may be disrupted during high-motion activities due to inconsistent skin contact or abrupt wrist movements, resulting in inaccurate heart rate readings (Hinde et al., 2021; Sarhaddi et al., 2022). These motion artifacts can introduce noise into PPG data and reduce the precision of heat stress monitoring.

These challenges highlight the need to refine smartwatch technology for more accurate physiological monitoring in real-world conditions. To improve the precision of heat stress detection, predictive algorithms should be integrated into commercial smartwatches to analyze real-time physiological and environmental data. Machine learning can help differentiate between physiological responses caused by heat stress and those induced by unrelated factors, such as physical exertion or anxiety. This integration would allow for more accurate and personalized heat risk assessments in high-temperature environments.

Additionally, ensuring regular sensor recalibration and software updates is essential for maintaining data accuracy over time. Users should be provided with instructions on how to properly calibrate and operate their smartwatch, and devices should offer automatic reminders based on usage patterns. In the context of heat stress detection, such enhancements can improve data quality and contribute significantly to the prevention of heat-related illnesses.

3.5 Predictive Models and Closed Feedback Systems for Heat Stress Prevention

The development of predictive models for personalized heat stress detection is crucial for preventing heat-related illnesses among outdoor workers. By leveraging machine learning and statistical techniques, heat stress events can be predicted and assessed in real time.

3.5.1 Predictive Models for Heat Stress Detection

The types of predictive machine learning models commonly found in the literature include decision trees, neural networks, and support vector machines (SVMs). Statistical approaches often utilize linear regression, logistic regression, and time-series models. Each model offers unique advantages and limitations in terms of the accuracy and reliability of heat stress detection. Machine learning models excel at identifying complex, non-linear relationships within physiological and environmental datasets, enabling real-time prediction. In contrast, traditional statistical models, including linear and logistic regression, provide simpler and more interpretable frameworks but may lack the adaptability needed for dynamic occupational environments (Kim et al., 2018; Shakerian et al., 2021).

3.5.2 Machine Learning Models

Machine learning models have been utilized in heat stress detection because of their ability to determine complex, non-linear relationships between physiological data, such as heart rate, heart rate variability, skin temperature and electrodermal activity, and environmental parameters, such as humidity, ambient temperature, and solar radiation. Because these models can dynamically adapt to individual variations based on physiological and behavioral differences, they enable a more personalized approach to heat stress prediction.

Neural networks offer key advantages in predicting individual heat stress responses, as they can handle large amounts of data and identify patterns. Input data, including physiological and environmental parameters, are processed through multiple layers, where it is transformed and weighted to generate predictions. As each layer is processed, data features are extracted, creating a more complex understanding of underlying patterns. In a case study, researchers from the University of California, Berkeley, used machine learning techniques, specifically neural networks, to create a model that could predict an individual’s heat stress response with over 90 percent accuracy (Liu et al., 2019). The model was trained using input variables drawn from both physiological and environmental data, including heart rate, skin temperature, ambient temperature, and humidity. Wearable sensors, such as the Polar H7 chest strap for heart rate, iButton for skin temperature, and a smartphone equipped with an accelerometer, were strategically placed on the body to provide real-time monitoring. The neural network successfully identified non-linear relationships between these data types, demonstrating its effectiveness in real-world heat stress detection.

Decision trees are a simpler type of machine learning model that use a series of binary decisions to generate predictions. Datasets are split into branches based on decision rules, and each branch represents a decision point, or node, defined by specific criteria. Starting at a root node, the model leads to a final prediction based on decisions made at each successive node. In heat stress prediction, decision trees are useful because they apply known thresholds in physiological parameters, such as heart rate and skin temperature, and environmental factors, such as ambient temperature and humidity. These thresholds are already well documented in the literature. Decision trees are valued for their transparency as their logic is easy to follow, making them helpful for understanding what factors most influence heat stress risk.

Researchers at Pennsylvania State University used a Random Forest model, which combines multiple decision trees, to predict heat strain in construction workers (Shakerian et al., 2021). The study included input variables such as electrodermal activity, skin temperature, and photoplethysmography, collected from wearable sensors. The Random Forest model demonstrated strong performance, achieving up to 95 percent accuracy in predicting heat strain.

SVMs, are supervised learning methods used for classification, regression, and outlier detection (Scikit-learn Documentation, 2024). SVMs are particularly effective for complex classification tasks. They function by determining the best boundary, or hyperplane, that separates groups of data points. When data is not linearly separable, SVMs apply mathematical transformations known as kernels to map data into higher-dimensional space, improving class separation. Setz et al. (2010) developed a personal health monitoring system using SVMs to detect stress during work-related activities (Setz et al., 2010). Electrodermal activity signals were collected from individuals in an office setting, and SVMs were used to distinguish between stress and cognitive load conditions. The model achieved a maximum accuracy of 82.8 percent. This result demonstrates the potential of SVMs to detect subtle physiological changes, supporting their use in real-time heat stress monitoring systems.

3.5.3 Statistical Models

As a more traditional method of detecting heat stress, statistical models, including linear regression analysis, logistic regression, and time-series models, are often utilized as a less complex technique compared to machine learning models to estimate the relationship between physiological responses, such as heart rate and core body temperature, and environmental conditions, such as ambient temperature and humidity. These models rely on historical data, including past weather conditions and recorded incidents of heat stress among workers. Additionally, they utilize pre-defined equations, such as the Heat Stress Index equation and the WBGT equations. The combination of both metrics allows these models to estimate heat stress risks based on input variables.

Despite their advantages in heat stress analysis, statistical models may not be capable of handling complex, non-linear relationships that occur within real-time data streams. For instance, the complexities present in rapidly changing physiological responses or environmental parameters may not be accurately captured using these models. In contrast, machine learning models can adapt to and learn from new data dynamically, making them more suitable for evolving conditions in occupational environments.

3.5.4 Measuring and Estimating Core Body Temperature

Core body temperature is one of the most important physiological parameters for detecting heat stress, as it directly reflects the thermal status of the body. Accurate measurement of core body temperature is difficult to obtain, which can be a challenge in dynamic occupational environments. Traditional techniques involve thermometric ingestible pills and rectal thermometers, which are highly accurate but impractical for real-time monitoring. Instead, many modern heat stress detection systems estimate core body temperature using physiological parameter signals collected through wearable sensors and predictive algorithms. Data obtained from wearable devices, such as skin thermistors, infrared sensors, or photoplethysmography sensors, help model body heat exchange dynamics. Machine learning algorithms, including neural networks, are used to correlate physiological parameters such as surface temperature and heart rate variability with core body temperature to provide real-time estimates. These estimates can be further improved by accounting for external environmental data, including ambient temperature and humidity, which allow predictions to be adjusted based on surrounding conditions.

3.5.5 Closed Feedback Loop Systems for Heat Stress Management

The integration of a complete real-time feedback loop with heat stress predictive models enhances the potential to influence infrastructure redesign aimed at reducing individual heat exposure and to inform policy adjustments that lower worker morbidity and fatality rates from heat-related illnesses. A closed feedback loop in a heat stress mitigation system involves relaying feedback to individuals when continuous monitoring of physiological and environmental parameters exceeds a threshold indicative of heat stress risk. Specifically, if heat stress thresholds are surpassed, a real-time alert mechanism can prompt immediate user intervention to reduce the risk of heat-related illness. This may involve actions such as relocating to a shaded area, hydrating with water, or adjusting workload intensity.

Depending on the system design, alerts can be auditory, visual, or verbal. In a study conducted by Mind Body Technologies LLC, the detection of abnormal physiological parameter levels triggered real-time feedback through a smartwatch, prompting users to modify their physical activities to avoid heat stress (Jerath et al., 2023). Real-time alert systems like this support a proactive approach to mitigating heat stress by enabling timely and personalized interventions.

Feedback loop systems can also be integrated into existing health and safety protocols to further improve worker protection. Combining predictive models with real-time feedback systems allows organizations to implement adaptive heat stress management strategies that respond dynamically to real-time data. For instance, wearable device data can inform supervisors of a worker’s heat stress level, enabling rapid adjustments to work-rest schedules or the deployment of additional safety measures. Another application includes crowdsourcing thermal sensation forecasts using geolocation data to improve the response time of emergency services for individuals at higher risk of heat stroke.

The development of predictive heat stress models combined with closed feedback loops presents significant opportunities for preventing heat-related illnesses. However, current technical challenges, such as ensuring model accuracy under varying environmental and individual conditions, mitigating sensor noise, and addressing data privacy concerns, must be resolved to strengthen the effectiveness of these systems in real-world applications. By addressing the absence of individualized, real-time feedback mechanisms in existing heat stress mitigation practices, this research establishes a foundational framework for proactive, data-driven heat stress prevention in a work setting.

3.6 Heat Stress Mitigation with Accounting for Individual Differences

Variations in individual factors can impact how a person experiences and responds to heat stress. Critical individual risk factors include age, physical fitness, hydration status, and acclimatization. Pre-existing medical conditions and certain medications can further reduce heat tolerance. Therefore, an individualized approach to heat stress mitigation is essential for optimizing personal safety and well-being.

Outlined below are key factors that contribute to varying levels of heat stress susceptibility among workers, emphasizing the need for personalized interventions:

- Age - Older adults and young children are more vulnerable to heat stress due to reduced sweat production, impaired cardiovascular function, and less efficient thermoregulation.
- Physical fitness - Workers with lower fitness levels face higher risk, as they may lack effective heat dissipation mechanisms, such as increased blood flow and elevated sweat rates.
- Acclimatization - Gradual exposure to heat can improve physiological responses, including more effective sweating and cardiovascular regulation, which reduce the risk of heat stress.
- Clothing - Heavy or non-breathable clothing can hinder the body's ability to cool itself by limiting sweat evaporation, increasing the likelihood of heat-related illnesses.
- Pre-existing health conditions - Individuals with heart disease, diabetes, respiratory infections, or those taking medications that impair thermoregulation may be more prone to heat stress.

Currently, most OSHA and industry heat stress protocols follow a one-size-fits-all approach. The ability to personalize mitigation strategies presents an opportunity to inform decisionmakers with evidence-based data, allowing for more flexible and tailored recommendations. For example, adaptive work-rest schedules or individualized hydration guidelines based on personal heat stress profiles may improve both worker safety and compliance with existing heat stress regulations.

4. IMPLEMENTATION CONSIDERATIONS

Smartwatch-based heat stress monitoring in outdoor work environments offers several advantages, including real-time, continuous physiological and environmental data that support early detection of heat stress. This enables early treatment of heat-related illnesses through immediate interventions. Additionally, the aggregation of smartwatch and environmental data can support long-term safety planning by identifying patterns in heat exposure, which may lead to more effective prevention strategies and a lower likelihood of injury.

Commercially available smartwatches, including those produced by Google, Garmin, and Fitbit, are capable of heat stress monitoring because they are equipped with features such as optical heart rate sensors, ECG sensors for heart rate variability, EDA sensors for skin conductivity, and accelerometers for motion detection. Many models also include sensors for oxygen saturation and skin temperature, along with Global Positioning System (GPS) functionality. Their affordability compared to medical-grade devices, combined with minimal physical obstruction, makes them a scalable option for widespread use.

To improve the detection and diagnosis of heat stress, multisensory systems that integrate smartwatch data with environmental monitoring instruments, such as portable Wet Bulb Globe Temperature monitors would be a valuable next step. These multifunctional approaches offer the benefit of combining physiological data with environmental inputs, such as humidity, wind speed, ambient temperature and solar radiation, which influence heat stress risk. This integration would allow for a more comprehensive evaluation of individual heat exposure and would promote a more personalized approach to heat stress management. Moreover, the reliability of smartwatch data in real-world conditions can be improved by applying machine learning techniques that filter noise and account for motion artifacts.

While there are logistical and technical challenges with the widespread adoption of smartwatches, including limited connectivity in remote areas and short battery life, these issues can be progressively addressed. Workshop-based training programs, participation incentives, and continuous engagement strategies can help overcome skepticism from workers and supervisors. Consistent training and proper device calibration are essential for successful implementation. Therefore, proactive heat stress management becomes increasingly feasible through the combined use of predictive machine learning models and integrated physiological and environmental monitoring. As these solutions continue to be developed and validated in practice, smartwatch-based monitoring will become more scalable and effective, enhancing safety across various industries and personal applications.

As a logical next step, a subsequent portion of this study focused on developing a conceptual design and small-scale field test of the technology application. This activity demonstrated promising results as to its potential application in an operational environment. Future plans call for an effort to operationalize the technology in a maritime setting and to evaluate its effectiveness. More specifically, the goal of a follow-up research project is to implement the application for maritime use such that the technology can alert workers and their supervisors in real-time about the onset of heat stress, provide immediate intervention, and contribute to the development of company-wide heat mitigation policy. This would help to determine the practicality of deploying smartwatch-based heat stress monitoring systems in such a challenging environment.

5. CONCLUSIONS

Heat stress mitigation research conducted to date underscores the potential of smartwatches and similar wearable technologies to significantly enhance worker safety in high-risk environments. These commercially available devices can provide real-time, personalized heat stress assessments by delivering tailored physiological data that help detect early signs of heat stress. By enabling timely interventions, such as rest breaks or hydration, smartwatches can help prevent heat-related illnesses before they become severe. Additionally, the integration of smartwatches into occupational health practices establishes a foundation for developing more effective regulatory frameworks that better protect workers from heat stress. These devices also support continuous monitoring and data collection, which is essential for refining predictive models and making assessments more individualized, considering factors such as age, physical fitness, and acclimatization.

This project has provided meaningful insight into the ability of an innovative technology that is commercially available at a modest cost to identify maritime transportation worker heat stress and mitigate heat stress risk to protect worker health and improve operational efficiency. It has established a framework for exploring opportunities to develop and implement risk mitigation strategies to better manage this threat. Study findings will fill a substantial knowledge gap at both the technical and practitioner level. Importantly, the work will advance proof-of-concept of a technology application with the potential for widespread adoption by the maritime transportation industry.

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