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Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices

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ABSTRACT

The construction process is considered a very risky endeavor because of the high frequency of work-related injuries and fatalities. The collection and analysis of safety data is an important element in measurement and improvement strategy development. The adoption of wearable technology has the potential for a result-oriented data collection and analysis approach to providing real-time information to construction personnel. The objective of this paper is to provide a comprehensive review of the applications of wearable technology for personalized construction safety monitoring. The characteristics of wearable devices and safety metrics thought to be capable of predicting safety performance and management practices are identified and analyzed. The review indicates that the existing wearable technologies applied in other industrial sectors can be used to monitor and measure a wide variety of safety performance metrics within the construction industry. Benefits of individual wearable sensors or systems can be integrated based on their attributes for multi-parameter monitoring of safety performance.

1. Introduction

The high rate of fatalities in the construction industry remains a major concern of both practitioners and researchers. Out of 4386 total worker fatalities in private industry in 2014, 899 were in construction, indicating that over one in five worker deaths are construction related [1,2]. Among industry sectors, workers in construction face the highest risk of occupational injuries and illnesses [3]. Despite the adoption of safety procedures and programs such as those developed and required by the Occupational Safety and Health Administration (OSHA), the rates of fatal and nonfatal construction injuries and illnesses have plateaued the past 10 years.

Given the high proportion of fatal and non-fatal accidents occurring in the construction industry, construction companies constantly seek novel strategies that promote safety [4]. Because of the transient and dynamic nature of construction, organizations must be able to quickly adapt to change by effectively capturing, storing, and disseminating new strategies that prevent injuries [5]. Thus, new technologies may be candidates for safety advancement. Although technology has undoubtedly played a major role in the improvement of construction processes, its application for personalized construction safety monitoring has not been fully explored [6].

In this paper, we review the various applications of wearable technology for personalized construction safety monitoring and trending. The specific objectives were to identify, catalog, and analyze attributes of wearable technology and resulting data thought to be capable of predicting construction safety performance and management practices.

2. Literature review

Due to the hazardous working environments at construction sites, workers frequently face potential safety and health risks throughout the entire construction process [7]. Construction safety has been traditionally measured and managed reactively by taking actions in response to adverse trends in injuries [8]. However, active monitoring of workers' physiological data with wearable technology may allow for measurement of heart rate, breathing rate and posture [6]. This section contains the review of relevant literature about safety performance monitoring, categories wearable systems and sensors as well as the applications of wearable technology in construction and other industries.

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2.1. Construction safety measurement and monitoring

Traditional approaches of measuring safety performance indicators are largely manual in nature and based on subjective opinions [9,10,11]. These approaches rely on massive manual data collection efforts; consequently, data are collected at low frequency (e.g., once a month) and when incidents occur [12,13]. These methods are costly, prone to data entry errors, and result in data sets that are too small for effective and successful project control [11]. To overcome the limitations of manual efforts, automated safety monitoring is considered one of the most promising methods for accurate and continuous monitoring of safety performance on construction sites [14]. Automated monitoring system can acquire data, convert it into structured data, and immediately deliver those data to project managers who can take action [15].

Among real-time project monitoring methods, a good number have strong applications for safety. The purpose of safety and health monitoring is to ensure there is effective measurement and management of construction workers safety practices against the existing safety plans and standards [7]. Unfortunately, the temporary nature of construction sites and project organizations makes the use of standard industrial monitoring systems impractical for construction [16]. Among other engineering application areas, automatically monitoring the location and trajectories of people can be useful for safety, security, and process analysis [11]. Wearable technologies in particular may enable the continuous monitoring of a wide range of vital signals which can provide early warning systems for workers with high-risk health issues [17,18].

2.2. Systems and sensors for wearable technology

Wearable technologies are based of different systems ranging from radio-frequency identification (RFID), magnetic field, radar, ultra-wide band (UWB), ultrasonic, sonar, Bluetooth, Global Positing System (GPS) (from Global Navigation Satellite System (GNSS)), laser, video and static camera, electrocardiogram (ECG/EKG), and electromyography (EMG). Sensors like galvanic skin response (GSR), accelerometers, gyroscopes, and magnetometers constitute a body sensor network. The evolution of digital and mobile technology has transformed many aspects of our lives with many examples that demonstrate the current and potential uses of wearable technology in the field of healthcare [19]. Innovations in sensor technology have been essential to the implementation of body sensor networks and have been combined with progress in short-range communication technologies such as ultra-wideband radio technology and Bluetooth which have enabled the implementation of wearable computing devices [20].

2.3. Wearable technology in other industries

Different categories of wearable technology have been applied across industries such as health care, manufacturing, mining, and athletics. Some of these technologies have shown signs of positive benefits [21] and efforts are being made by both researchers and industry experts to improve on these technologies and learn from their initial implementation.

With the advent of computing platforms with low power consumption and low cost sensors, wearable technology has been increasingly used in health-related research to promote physical activity [17]. Significant progress in computer technologies, solid-state micro sensors, and telecommunication has advanced the possibilities for individual health monitoring systems to collect and analyze human physiological metrics. A variety of compact wearable sensors are currently available [18,22]. Advances in miniature sensors and wireless technology have made available a new generation of monitoring systems that allow one to record physiological data from individuals carrying on daily activities in the home and outdoor environments [23]. Similarly, remote patient monitoring allows people to keep track of their health while avoiding unnecessary visits to the doctor.

In the business sector, several companies took inspiration from the seminal work achieved by researchers at the National Aeronautics and Space Administration's Jet Propulsion Laboratory (NASA-JPL) and developed systems-based body sensor networks for commercialization [18]. One such device provides wellness applications, wireless activity monitors, and health tracking devices that continuously track data such as heart rate, activity, respiration, body temperature, and posture in order to lower healthcare costs and increase productivity [24,25]. These applications are geared toward increasing knowledge transfer, productivity, and security within business operations including controlled access, customer services, remote supervision, and stock allocation [22,26].

In sports and fitness, wearable technologies are being used widely for tracking performance through the smooth and unobtrusive measurements [27]. Wearable technologies such as the GPS watches, heart rate monitors and pedometers are commonly used to obtain real-time information about performance [27,28]. Wearable technology is being incorporated into a multitude of equipment used by professional athletes to monitor not only their performance, but also their safety [29]. For example, sensors are used in the helmets of National Football League (NFL) players to detect concussions and smart compression shirts that have been wired to measure arm movement and technique to determine a pitcher's effectiveness in Major League Baseball (MLB). Also, wristband wearable GPS sport watches are commonly used in the game of golf during practice sessions to improve swing mechanics [21]. Others existing applications of wearable technologies in sport and fitness sector are related to an active lifestyle, including fitness monitoring, outdoor navigation, body cooling and heating, virtual coaching, and sport performance [22].

In security applications, police officers, firefighters, and paramedics are testing wearable technologies to provide remote communication support and feedback with the ability to access information hands-free while carrying out essential tasks [30]. Additionally, for personal security, lighting technologies and protective clothing are being used to enhance visibility and attract attention.

In the mining industry, a proximity warning system (PWS) based on the GPS and peer-to-peer communication was also developed to prevent collisions between mining equipment, small vehicles, and stationary structures [31]. The concept of GPS-based proximity warning for mining equipment entails the use of differential GPS receivers so that the equipment operators are aware of other vehicles or workers nearby.

Wearable technologies are also increasingly influencing people's daily activities in terms of gaming and in the tools used to operate household devices or other gadgets used in communicating [27]. This involves applications related to interacting with computing resource, including data/media access, interactive gaming, responsive learning, and shared experience [22].

2.4. Wearable technology in construction

As opposed to other industries, the application of wearable technology in construction is at the nascent stage. In fact, there are very few documented cases of application of wearable technology in the construction industry [6]. One of the very few application was the evaluation of a method for testing proximity detection and alert systems to promote safety on construction sites [32–34]. Also, hands-free systems were employed to monitor workers and increase their situational awareness by continuously collecting data on the jobsite, detecting environmental conditions, and the proximity of workers to danger zones [35]. The lack of wide-spread implementation is due, in part, to a lack of reliable data supporting their potential benefits.

Recently, the construction industry has begun to use mobile devices to access and share project data from remote work sites [36]. Although, the construction industry may be slow in adopting trends in mobility

Table 1
Safety performance metrics for construction safety and health hazards.

	Construction site hazards		Metrics
	Safety hazards	Health hazards	
Physiological monitoring	Slips, trips, and falls from height.	Stress, heat, cold, strain injuries (carpal tunnel syndrome, back injuries), skin diseases (absorption), cuts (injection), breathing or respiratory diseases, toxic gases.	Heart rate, heart rate variability, respiratory rate, body posture, body speed, body acceleration, body rotation and orientation, angular velocity, blood oxygen, blood pressure, body temperature, activity level, calories burn, and walking steps.
Environmental sensing	Slips, trips, fire and explosions.	Chemicals (paints, asbestos, solvents, chlorine), molds, noise, heat, cold, radiation, vibration, toxic gases.	Ambient temperature, ambient pressure, humidity, noise level, light intensity, air quality.
Proximity detection	Caught-in or -between, Struck-by moving vehicle or equipment, electrocution.	Chemicals (paints, asbestos, solvents, chlorine), molds, noise, heat, cold, radiation, vibration, toxic gases.	Object detection, navigation, distance measurement, and proximity detection.
Location tracking	Caught-in or -between, struck-by, confined spaces, cave in, electrocution.	Hazardous chemicals (paints, asbestos, solvents, chlorine), molds, noise, heat, cold, radiation, vibration.	Worker location tracking, materials tracking, and vehicle/equipment location tracking.

and automation tools, and other technologies that can increase efficiency [36], wearable technologies could uncover possibilities for improvement in construction [37]. Thus, there is great potential for the implementation of wearable technology for personalized safety monitoring in the construction industry.

2.5. Research needs statement

In the construction industry, workers are exposed to hazards that are difficult to measure for reasons closely related to the way construction tasks are executed. Not only does the location for any group of workers change, each construction site evolves as construction proceeds, changing the hazards workers face on daily basis [38]. Most of the existing data collection approaches are manual and are faced with major challenges related to accurate recording, interpretation, and efficiency [11]. Wearable technologies offer a non-intrusive solution that provides objective, real-time data that can be used to make efficient and proactive decisions. Wearable technology adopts a concept of a safety management system that enables workers to monitor and control their health profile via real-time feedback, so that the earliest signs of safety issues arising from health problems can be detected and corrected [39]. Wearable sensors can also provide safety mangers with quantitative measures of subjects' status on construction sites thus facilitating decisions making concerning the adequacy of ongoing interventions and possibly allowing prompt modification of the strategy if needed [18]. Despite the potential benefits of such strategies, few have been identified in the literature and there is yet to be an organized effort to codify and investigate these methods [8].

This paper contributes to the body of knowledge by providing a comprehensive review of wearable technology systems and examining their application potentials for personalized construction safety monitoring and trending. This study also provides an evaluation of the features of wearable devices, the safety data that can be obtained, and the potential benefits of using wearable technology to mitigate injuries and illnesses on construction sites.

3. Methods

This research was conducted by first reviewing the present state of knowledge of wearable technologies across industries, codifying literature and specifications related to each candidate technology systems and sensors, and describing the human factors implications of the technologies in accordance with prevailing theory. The construction safety and health hazards were reviewed to identify the metrics that can be captured and processed by the wearable technologies to measure and monitor safety performance. The literature review revealed four divisions of measurable safety performance metrics: 1) physiological monitoring; 2) environmental sensing; 3) proximity detection; and 4) location tracking. A comprehensive review of each of these four divisions, the safety performance metrics that can be measured and monitored, and the applicable wearable technology systems and sensors is presented. Additionally, commercially available wearable technologies were critiqued based on the performance characteristics required of functional personalized wearable devices. An online search was carried out to identify the leading manufacturers of wearable technologies as well as documented research works on wearable technology applications across the globe. Information about wearable devices from the manufacturers' specifications documents and published research works were collected and evaluated. A model for the integration of the different wearable systems and sensors into the design of functional wearable devices for personalized safety performance monitoring in construction was also presented and discussed.

4. Results and discussion

The results of this review study are presented and discussed in different sections based on the research methodology framework. Critical findings of each review, including the wearable technology systems and sensors thought to be the most promising for applications in construction safety monitoring and trending, are presented.

4.1. Construction safety and health hazards

About 6.5 million people work at approximately 252,000 construction sites across the U.S. on any given day [3]. These workers are exposed to a variety of safety and health hazards everyday increasing the potential for becoming sick, ill, and even disabled for life. The fatality injury rate for the construction industry is higher than the national average in this category for all industries [3,40]. Injury and illness rates on construction sites have been on the rise over the years [41]. Some of the potential safety and health hazards for construction workers include: falls from height due to improper erection of scaffolding or use of ladders; repetitive motion injuries; heat exhaustion or heat stroke due to body temperature rising to dangerous levels; and struck by moving equipment working in close proximity to workers [3]. Table 1 presents these safety and health hazards as well as the measurable metrics associated with the hazards. The corresponding divisions of the measurable safety performance metrics are also provided for proper deployment of wearable technologies for the collection and analysis of the metrics required for the mitigation of the hazards. Table 2 also illustrates the sensors and systems for monitoring the common safety and health hazards associated with the construction

Table 2
Sensors and systems for monitoring common construction safety and health hazards.

Construction Site hazards	Metrics	Sensing technology
Falls from height	Body posture	Gyroscope, accelerometer, magnetometer
Slips and trips	Body posture, body speed, body rotation and orientation	Gyroscope, accelerometer
Stress	Heart rate, blood pressure, respiratory rate	ECG/EKG, infrared, radar
Heat or cold	Body temperature	Thermistor
Fire and explosions	Smoke and fire detection	Infrared
Noise	Noise level	Noise sensor
Caught-in or -between	Proximity detection	RFID, UWB, infrared, radar, Bluetooth
Struck-by object	Proximity detection, location tracking	RFID, UWB, infrared, radar, Bluetooth, GPS
Electrocution	Proximity detection, location tracking	RFID, infrared, radar, Bluetooth, GPS, RFID, UWB
Cave in	Location tracking	GPS, RFID, UWB

process.

4.1.1. Physiological monitoring

One application of wearable systems is the monitoring of physiological parameters in a mobile environment [42]. For instance, wearable devices targeting the sport and recreational market have been very successful. Wearable devices offer many benefits to professional athletes, amateur athletes, fitness consumers, and wellness programs. Some of these benefits include player safety assessment tools, workout injury prevention, and metrics of physical conditioning and performance [21]. Recent technological advances in integrated circuits, wireless communications, and physiological sensing allow miniature, lightweight, ultra-low power, and intelligent monitoring devices for health monitoring. A number of these devices can be integrated into a Wireless Body Area Network (WBAN), a new enabling technology for health monitoring [43].

Construction site workers often encounter various health risks as a result of the austere and dynamic work environments which can impact the safety performance and overall performance of construction workers [44,45]. Commercially available physiological status monitoring (PSM) systems can reliably collect physiological properties of people in outdoor environments [45]. However, it has been demonstrated that physiological data such as heart rate, breathing rate, body posture, body speed, and body acceleration can be automatically recorded and analyzed using a PSM system and GPS tracking device to assess construction equipment operator's health [46,47]. An extensive set of physiological sensors may include an ECG/EKG (electrocardiogram) sensor for monitoring heart activity, an EMG (electromyography) sensor for monitoring muscle activity, an EEG (electroencephalography) sensor for monitoring brain electrical activity, a blood pressure sensor, a tilt sensor for monitoring trunk position, a breathing sensor for monitoring respiration, and movement sensors used to estimate user's activity [43].

Based on the commercially-available wearable technologies reviewed, the ECG/EKG sensors seem to have wider use in the monitoring and measurement of physiological metrics. The ECG/EKG measures heat rate, heart rate variability, respiratory rate, blood pressure, and body temperature. An electrocardiogram (ECG or EKG) is a test that checks for problems with the electrical activity of the heart. It shows the heart's electrical activity as line tracings on paper. It is one of the most widespread system for the monitoring of the cardiac activity and the information provided by ECG is related to heart electrical activity [48]. Our review also shows that infrared technology is another system used in wearable sensors to monitor and calculate heart rate, analyze activity level, and track fitness performance. Infrared wireless is the use of wireless technology in devices or systems that convey data through infrared radiation. Infrared is electromagnetic energy at a wavelength or wavelengths somewhat longer than those of red light. According to our review, the commercially available infrared sensors are often used in conjunction with Bluetooth technology for connectivity and they are compatible with common operating systems for mobile devices such as Android and iOS. For example in the smart shirt technology, the Bluetooth technology enables the data detected from the smart shirt to be delivered to the Personal Digital Assistant (PDA) and analyzed [49]. Radar systems have also been used in the monitoring of the heart activity in a noninvasive and contactless way for the patient. Microwave Doppler radars have been used to detect the respiratory rate [48].

A gyroscope may be used to determine the rotation of different parts of the body. Our review indicates that gyroscopes monitor activity by measuring body rotation and angular velocity while magnetometers (i.e. magnetic field sensors) are useful in determining orientation relative to the earth's magnetic north. The gyroscope, accelerometer, and magnetometer are usually combined because each of the sensors has its own unique strength. For instance, a magnetometer has poor accuracy for fast movement but with zero drift over time while gyroscope reacts quickly to changes. Recently, some inexpensive in-chip inertial sensors including gyroscopes and accelerometers have gradually found practical applications in human motion analysis [50]. The technology of Micro Electro Mechanical Systems (MEMS) boosts the development of miniature and low-powered inertial sensors, accelerometers and gyroscopes, to analyze human movement based on kinematics [51]. Gyroscope sensors have been used as wearable devices to determine the peak of the upper arm internal rotation, wrist flexion, and shoulder rotation during the forward motion of tennis athletes, a skill assessment and acquisition tool [52]. Gyroscopes appear to be more reliable in the measurement of angles, therefore, can more accurately identify functional activities and the emerging movement patterns [53]. In addition, it has been argued that the combination of different technologies provides the most optimal activity monitor platform.

Patel et al. [54] reported that when wearable sensors are used to improve balance control and reduce falls, data analysis procedures could be exclusively developed to detect falls via processing of motion and vital sign data. In this situation, ambient sensors could be used as wearable sensors to improve the accuracy of falls detection [54]. Bourke et al. [55] used tri-axial accelerometer embedded in a specially made vest to detect falls while Bianchi et al. [56] implemented a barometric pressure sensor as an alternative measure of altitude to differentiate real fall events from normal activities of daily living. Yavuz et al. [57] also developed a fall detection system that relied upon the accelerometers available in smart phones and incorporated different algorithms for robust detection of falls. Some researchers have also developed an automatic fall detection system in the form of a wrist watch [54]. This device implements functionalities such as wireless communication, automatic fall detection, manual alarm triggering, data storage, and a simple user interface [54].

The evaluation of the existing wearable technologies also reveals that there is a limited application of ultrasound technology for the monitoring of physiological metrics in construction. For example, Lewis et al. [58] designed and evaluated a wearable self-applied therapeutic ultrasound device that can be worn by construction workers on their shoulder to reduce chronic myofascial pain. Ultrasonic sensors have also been developed for monitoring muscle contraction.

The review also identified the capabilities of ANT + in enabling effective communication between wearable systems for the monitoring of physiological metrics (such as heart rate, calorie burn, and workout). ANT + is a wireless sensor network protocol, designed to enable communications between self-powered devices in an extensible network environment, easing the collection, automatic transfer and tracking of sensor data for monitoring of all personal wellness information [59]. ANT + aides the devices to interoperate and build an ecosystem by implementing device profiles which are ANT + protocol branded standards [60]. Current ANT + profiles are available for the following devices: heart rate monitor, foot pod, bicycle speed and cadence, bicycle power, weight scale, multi-sport speed and distance [59]. With ANT +, multiple applications can be run simultaneously using different sensors. For instance, running distance can be tracked with one application while blood glucose level is concurrently monitored with another application.

4.1.2. Environmental sensing

The nature of construction work environment is such that poses both health and safety risks to workers. This is not only because most of the activities are performed outdoors making workers experience considerable exposure to weather elements, but the construction processes also involve the use of hazardous materials in form of chemicals, gases, and solid materials. Automated sensing of these injurious materials and inclement weather elements is necessary. The monitoring of environmental parameters in a diffused fashion is of paramount interest in various fields of endeavor; for example, for environmental safety, health, and security purposes. A lot of work has been completed on the development of smart sensors and wireless sensor networks based on silicon technology, targeting different types of application [61]. For instance, making sensors small, Bluetooth or Wi-Fi enabled, and easily worn by workers performing their normal daily activities can considerably increase the amount and precision of environmental data [62], particularly in the construction environment which is ever-evolving.

More generally, it is now possible to use environmental sensors to measure a range of concerns including air quality, barometric pressure, carbon monoxide, capacitance, color, gas leaks, humidity, hydrogen sulfide, temperature, and light [63]. The capacitive sensor has been applied in different systems as a stud finder, a liquid level monitor, or a proximity monitor. Various sensing principles have been integrated on a polyimide foil, such as capacitive and resistive read-outs for the detection of several types of environmental parameters including temperature, humidity, reducing and oxidizing gases, and volatile organic compounds (VOCs) [61]. These sensors on plastic foils are required to realize intelligent RFID tags for environmental monitoring.

There are also integrated environmental sensors that support a broad range of emerging high performance applications such as navigation, barometric air pressure, humidity, ambient air temperature sensing functions as well as air quality measuring (Bosch [64]). Some of these sensors are specifically designed for various applications in the field of mobile devices and wearable technologies, and can be implemented in construction. Workers can be monitored while doing their normal work while at the same time having the ability to see highly localized, real-time data on things like temperature, hazardous gases, and particulate levels in the air and even detect toxic chemical leaks [62]. Other environmental sensors that can be used in wearable devices are gyroscope, light sensors, noise sensors, humidity sensors, temperature sensors, gas sensors, among others [65].

4.1.3. Proximity detection

Considering the high rate and severity of contact injuries, there is need for strategic monitoring and analysis of the states of construction entities so that potential collisions can be prevented in a timely manner [34]. The construction industry needs a wireless, reliable, and rugged technology capable of sensing and alerting workers when hazardous proximity issues exist [33]. Moreover, the advancements of sensing technologies greatly prompt the development of collision avoidance systems [34]. A real-time proximity detection and warning system capable of alerting construction personnel and equipment operators during hazardous proximity situations is needed to promote safety on construction sites [33].

Many proximity avoidance systems have been developed by utilizing various technologies, such as an ultrasonic-based sensor [66], radio frequency (RF) sensing technology [67,68], radar [66,69], and a GPS [70] to prevent contact accidents, particularly for accidents due to being struck by equipment.

Our review of the existing wearable technologies shows RFID to be the most commonly used system for proximity detection. RFID is the projection of radio waves and signals to transmit data and conduct wireless data retrieval and storage to identify the status of workers and object contents [71]. It consists of two components, a unique identification tag installed onto or into the object to be identified and a reader or tag detector that senses for the unique transmitted frequency and ID of a tag [72]. No direct contact between a RFID reader and the tagged item is needed as it uses radio wave which can be classified as low, high, ultrahigh frequencies (UHFs) ranging from 125 kHz to 5.875 GHz. According to Roberts [73], three frequency ranges are generally used for RFID applications. In general, low-frequency passive tags have an effective range of approximately 30 cm, high-frequency passive tags around 1 m, and UHF passive tags from 3 m and 5 m. Where greater range is needed, such as in container tracking and railway applications, active tags can boost the signal to a range of 100 m. Our review also indicates that a wearable RIFD technology could have up to 500 m (1500 ft) read range. This "read range" is far greater than the 15 to 25 m obtained from the RFID technology 10 years ago by Goodrum et al. [74] in their study. In addition to reading data, it is possible to write data back to the RFID tag, which greatly increases the interaction between items, system, and people. The principal advantages of RFID system are the non-contact, non-line-of-sight characteristics of the technology. Tags can be read through a variety of visually and environmentally challenging conditions such as snow, ice, fog, paint, grime, inside containers and vehicles and while in storage [73]. All these advantages enable a better real-time information visibility and traceability [75].

UWB also proves to be another effective technology used in wearable technology systems for proximity detection. UWB uses short nanosecond bursts of electromagnetic energy in the form of short pulse radio frequency waveforms over a large bandwidth less than 500 MHz [76]. Compared to RFID technology, UWB transmits data over a large bandwidth, which makes it less prone to signal interference and easier to pass through walls [32]. UWB has been proven to possess unique advantages including: longer range, higher measurement rate, improved measurement accuracy, and immunity to interference from rain, fog, or clutter when compared to other technologies like RFID or ultrasound [77]. The distinct advantages of UWB technology make it ideal for a variety of applications on construction sites, either independently or as part of an integrated system with one or more of the other available tracking and monitoring technologies [78].

The other technologies used in wearable devices for proximity detection are radar, magnetic field, ultrasound, GPS, sonar, and Bluetooth. Ultrasound has the possibility for precise measurement but is the science of sound waves above the limits of human audibility. Ultrasonic sensors produce ultrasonic frequencies (between 16 kHz and 1 GHz) that humans cannot hear, making them ideal for quiet environments. They consume less energy or power, are simple in design, and are relatively inexpensive. While ultrasonic sensors exhibit good resistance to background noise, they are still likely to erroneously respond to some loud noises. Proximity ultrasonic sensors require time for the transducer to stop ringing after each transmission burst before they are ready to receive returned echoes. Thus, sensor response times are typically slower than other technologies at about 0.1 s. Density, consistency, and material as well as changes in the environment such as temperature, pressure, and air turbulence can distort an ultrasonic sensor's readings.

Magnetic field generators can be used to establish magnetic fields around an equipment. A sensor worn by a worker provides a measurement of the magnetic flux density that is used to estimate the proximity to the machine [79]. In the operation principle of magnetic proximity detection systems, a sinusoidal (or modulated) current at a carrier frequency between 10 kHz and 100 kHz flows through a generator consisting of a wire coil wound around a ferrite core to establish a magnetic field [79]. A magnetic sensor worn by a worker detects the magnetic signal and measures the magnetic flux density on three orthogonal axes. These readings are used to calculate the total magnitude of the magnetic flux density which is then used to estimate the distance from the machine. When compared with other technologies adopted for unsafe-proximity detections, a GPS-aided Inertial Navigation System (INS) sensor has the advantages of ease of use and high accuracy in performance. A GPS-aided INS sensor can provide 3D position, speed, and orientation directly to meet the demands of the model; these measures can be considered as a limitation of technologies such as ultrasound, infrared, and RF sensing technologies [34].

Most of these technologies provide some form of warning signals to workers when they are close to heavy equipment. These signals could be visual, vibratory, or audible warning signals. The choice of the type of signal chosen is also dependent on the type of task being carried out on the construction site. These proximity zones could either be within warning zones with limited risks or within danger zones which constitutes regions of high risks.

4.1.4. Location tracking

Various tasks in the planning, designing, and execution phases of construction projects heavily rely on a wide range of location data, such as worker and equipment location data for safety planning and management, and material location data for progress tracking [32]. Effective planning and control for complex construction projects requires reliable material tracking, effective supply chain visibility, and accurate progress estimation [78]. Accurate, reliable, and frequent information about the location of equipment, materials, and workers can help the manager to make the best decision possible based upon actual conditions [80,81]. Locating and tracking resources is critical in many industrial applications for monitoring productivity and safety. In construction, various technologies such as GPS, RFID, and radio frequency (RF) localization have been proposed for monitoring safety performance [76]. All these applications highlight the importance of real-time location and progress tracking technologies [78].

Localization and tracking technologies have been applied to identify undetected obstructions in blind spots [82] and have also been utilized in the tracking of workers to manage factors related to human error such as lack of hazard recognition [83]. The accuracy of localization and tracking is heavily influenced by signal availability, but it is very difficult to maintain enough signal availability on construction sites [84]. Localization techniques, in general, utilize metrics of the received radio signals (RRSs). The most traditional received signal metrics are based on measurements of angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), or received signal strength (RSS) from several reference points (RPs). The reported signal metrics are then processed by the positioning algorithm for estimating the unknown location of the receiver, which is finally utilized by the application. The accuracy of the signal metrics and the complexity of the positioning algorithm define the accuracy of the estimated location [85].

Our evaluation of existing wearable technologies proves GPS to be the predominant technology used for location tracking. GPS technology is one of the most promising and attention-drawing techniques utilizing satellites to precisely locate coordinates [49]. The system consists of three prime components: 1) GPS satellites, 2) earth control, and 3) user receiver. Apart from its use for location and tracking of resources, it has been used in proximity warning systems to prevent collision between workers and equipment. GPS is a well-known satellite-based positioning system used for tracking users in outdoor environments [85], although it lacks the capacity to penetrate indoor environments [86].

This review also identified UWB as another sensing technology for precise location tracking in construction. It is of the widely used wireless network technologies for real-time location system and has been found to be the most reliable and accurate real-time indoor position tracking technology compared with Wi-Fi and wireless mote sensors [87]. UWB technology is a tag-based sensor technology for tracking multiple resources. Little post-processing is required since workers' 2D or 3D trajectories are actively sensed through wearable tags [88]. The UWB system is a network of receivers and tags communicating with each other over a large bandwidth greater than 500 MHz. The tag transmits UWB radio pulses that enable the system to find its 3D position coordinates [78]. Unlike other technologies, it is less prone to signal interference and easily passes through obstructions because it transmits data over a large bandwidth.

RFID technology is used in many industries for asset tracking, proximity detection, and security applications. RFID technology has been used in the health care industry to improve patient monitoring and safety, increase asset utilization with real-time tracking, to reduce medical errors by tracking medical devices, and to enhance supply-chain efficiencies [89]. Other technologies used for location tracking to a very minimal extent are sonar, magnetic field, and radar.

4.2. Performance characteristics of wearable technologies

Wearable devices are expected to have some performance characteristics or meet certain design criteria necessary for their optimum operation. Some of these characteristics (or variables) include size and weight of sensors, power source, computation capability, sensor location and mounting, and wireless communication range and transmission. The review of the performance characteristics thought to be relevant in the design and choice of wearable technologies for applications in construction is presented as follows.

4.2.1. Size and weight of device

The size and weight of a device are certainly part of the most important attributes considered in the design and choice of wearable technology because a device must be small and lightweight before it can be considered wearable. The issue of size and weight particularly becomes more significant in the use of wearable devices by construction workers who usually carry a few necessary tools needed to execute their task. In order to also achieve non-invasive and unobtrusive continuous monitoring of workers' health and activities, wireless sensors must be lightweight and small. Wearable devices should be: small enough to fit on any asset without interrupting the completion of work objectives [77], and best incorporated into the gadgets (such as watches, wristbands, reflective vests) normally worn by the workers.

It is however important to note that a battery's capacity is directly proportional to its size. This means that the size and weight of sensors is predominantly determined by the size and weight of batteries [43,90,91]. Also, the requirements for extended battery life directly oppose the requirement for small size and low weight. The sizes of the wearable technologies reviewed ranged from 1.67 in. by 1.32 in. by 0.43 in. to 4.8 in. by 2.31 in. by 0.56 in. which means they are not obtrusive or conspicuous. This enables the devices to gain efficiency and become more powerful. As pointed out by Darwish and Hassanien [28], one can expect that further development of technology and advances in miniaturization of integrated circuits and batteries will help developers to decrease the overall size of wearable sensors.

4.2.2. Power source

Power source, power consumption, and energy efficiency are important factors also considered in the design and selection of wearable technologies. The operating profile of wearable devices differs significantly from mobile devices like smartphones. Much of the time a device is in ultra-low power standby-mode and at different times wakens to active-mode where power consumption is much higher [21]. Wearable sensors have to be extremely power efficient, because frequent battery changes for multiple wearable sensors would likely hamper users' acceptance and increase the cost [43]. Furthermore, low power consumption is very important as we move toward future generations of implantable sensors that would ideally be self-powered, using energy extracted from the environment. To better manage power consumption, direct memory access can be power-optimized with a dedicated Peripheral Management Unit (PMU) [21].

Diligent power and battery management design techniques are needed to achieve ultra-low operating power and long operating life from the smaller size and lower capacity batteries used in wearable devices. Also, intelligent on-sensor signal processing has the potential to save power by transmitting the processed data rather than raw signals, and consequently to extend battery life [43]. The technologies also have varying operating voltage and power consumption. Since most construction activities are performed outdoors, wearable devices that use alternative power source such as solar cells can be developed. A notable company has launched clothing with solar cells to charge devices. The clothing can simply be adapted to function as reflective vest worn by construction workers. Kinetic energy-powered gadgets which can be used by mobile workers have also been developed while body heat has been used to power small light-emitting diode (LED) lights on a ring.

4.2.3. Sensing and sensitivity of device

The process of sensing in a wearable device is generally accomplished by sensors which collect data that can be passed to the storage system if present [17]. A personal server can then be used to collect sensor readings, process and integrate data from various sensors, provide better insight into the users' state, and then provide an audio and graphical user-interface that can be used to relay early warnings or guidance, and secure communication with remote servers in the upper level using Internet services [43].

The sensitivity of the sensor devices is especially important when users wear these sensors in harsh environments such as the construction environment. The heavy equipment, materials, and structures typically found on construction sites may impact the sensitivity of these wearable devices. Sweat produced by construction workers can also affect the transducers of the sensor devices negatively, causing a reduction in the sensitivity of the body-worn sensors or requiring recalibration of the sensors [28]. For instance, sensitivity to sunlight and need for line-of-sight are shortcomings of infrared when it comes to its application in construction. Also, magnetic field may be interfered by metallic objects in the environment, which can decrease the accuracy of measurement [92]. These issues are considered in the choice of technology system for developing wearable devices because technologies that are not affected by these conditions would be favored over other ones. Additionally, there is need for the designers of these wearable devices to improve their designs and ensure the devices provide maximum resistance to the interference that might be encountered on construction sites.

4.2.4. Multi-parameter monitoring

As discussed earlier in this paper, several safety performance metrics are required to be measured and monitored using different wearable technologies or sensors to mitigate the safety and health hazards associated with the construction process [3]. The existing applications of wearable technologies in construction and other industries have demonstrated that wearable technology systems are capable of measuring multiple parameters all in a single device. For instance, multiple physiological sensors used to monitor similar metrics such as heart rate, heart rate variability, and respiratory rate can share a single wireless network node. In addition, physiological sensors can be interfaced with an intelligent sensor board that provides on-sensor processing capability and communicates with a standard wireless network platform through serial interfaces [43]. The ANT + protocol also permits interoperability between different sensors which enables the simultaneous tracking of different metrics using one system. From the commercially-available wearable devices reviewed, some of the physiological monitoring technologies such as ECG/EKG and gyroscope are used in conjunction with the GPS technology to concurrently track the location of the user. The Bluetooth technology is also used in conjunction with some of the other technologies for connectivity.

4.2.5. Accuracy and precision

Accuracy is defined as the statistical difference between the estimate or measurement of a quantity and the true value of that quantity [93] while precision is how close the measured values are to each other. For instance, location accuracy is how much the estimated position is deviated from the real position while precision is the percentage of time the location system provides the given accuracy [94]. Wearable technologies should be capable of accurately and precisely recording the activities that are associated to monitored work tasks [77]. This is one of the major advantages the application of wearable technologies for data collection and analysis has over the human errors that might be involved in the traditional approach.

According to reported findings and specifications published by the manufacturers of the wearable devices evaluated, the accuracy of selected wearable devices for proximity detection defined by the percentage of measured detection distance to the true distance varies between 95.0 and 99.0% for magnetometer and Bluetooth respectively (Fig. 1). Also, the percentage accuracy of a location tracking wearable device based on GPS defined in terms of the pseudorange (i.e. an approximation of the distance between a satellite and a GNSS receiver) was reported to be 95%.

4.2.6. Storage

Storage is required in order to collect and store data so that the derived information can be made available from the processed data [17]. Wearable devices need more memory capacity because of the increasing number of sensor elements, the need for mobile software applications, and the rise of edge analytics [21]. More sensors create more data volume which increases communication network traffic between wearable devices and edge access points. The data throughput over local area networks must be minimized to reduce communication link congestion. By moving analytics processing closer to the device, there will be less network data traffic and by nature less congestion which is one of the primary benefits from edge analytics [21]. The device should be able to perform an analysis of all measurements online, presenting them in appropriate form to both wearer and remote base station [42]. The data collected by using the existing wearable

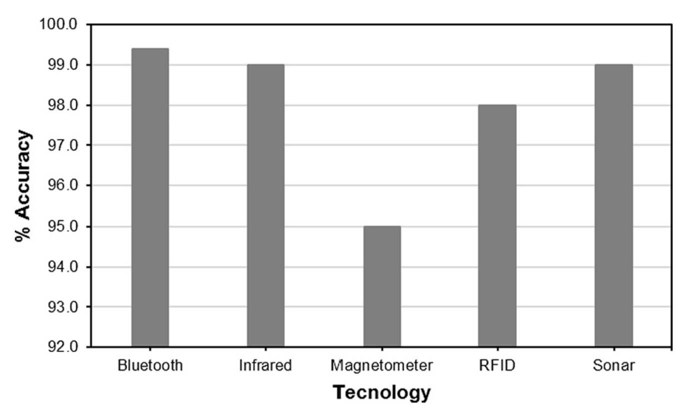

Fig. 1. Accuracy of selected proximity detection wearable devices.

technologies is usually stored either on the wearable device or more accurately in its cloud software. The storage of data collected with wearable devices is a serious concern because high risks might be involved if the data is carelessly stored and then stolen through a data breach by a mischievous third party.

4.2.7. Device location and mounting

Although the purpose of the measurement does influence sensor location, researchers seem to disagree on the ideal body location for sensors [43]. In general terms, the closer the wearable device is to the signal it is collecting, the stronger the accuracy. This means that a wearable sensor worn for example on the chest can sense heart signals with high accuracy. Commercially available wearable devices come in form of smart wristbands, watches, shirts, headbands, necklaces etc. Although there is a rising number of wearable devices attached to the body, worn on head or around the neck, most wearable devices are commonly worn on the wrist. Wristband wearable devices have the highest consumer interest level and this is evident in the mounting positions of the wearable technologies evaluated. Recently, the integration of wearable devices into jewelry such as watches, pendants, and rings has been on the rise. Other examples of miniature wearable devices are skin-worn wearable patches which are secured directly on the skin preventing the need for straps, buckles or bands. These body-worn patches come in variety of forms ranging from transparent films on the skin to miniature shells that stick to various parts of the body. To increase the acceptance of wearable devices by construction workers, the devices should be incorporated into clothing or gadgets (such as safety vest, shoes, watches, and wristband) normally worn by the workers on daily basis.

4.2.8. Cost and maintenance

Wearable technologies should have low implementation and maintenance cost, while being rugged enough to withstand a harsh environment and project lengths of up to several years [77]. The cost of wearable devices is hinged on many factors ranging from the metrics to be assessed, the sensors used, hardware requirements, power source, etc. From the commercially-available wearable technologies reviewed, the cost of selected wearable devices for proximity detection ranges from $35 for Bluetooth to $1159 for RFID as shown in Fig. 2.

4.2.9. Frequency band

To enhance operations and communications on a harsh and dynamic construction site, there is need for an appropriate frequency band for efficient wireless networking. Frequency band greatly influences the accuracy of distance and speed measurements. For instance, a high frequency signifies that more vibrations are produced than it is for a low frequency over the same time. This implies that high frequency produces a higher speed because of low amplitude. Therefore, higher reading range and speed are achieved when the frequency is increased

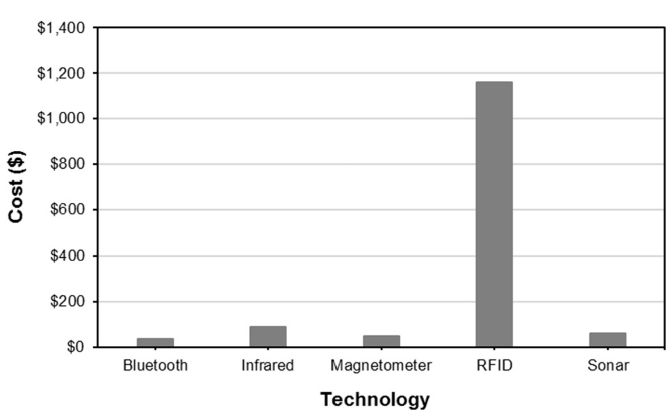

Fig. 2. Cost of selected proximity detection wearable devices.

[84].

4.2.10. Social issues

Social issues of wearable systems include privacy, security, and legal issues. Due to communication of health-related information between sensors and servers, all communication over wireless network of wearable computing devices and internet should be encrypted to protect user's privacy [43]. Wearable devices are vulnerable to security threats, hence, strong security measures are critical to protect against malicious attacks that can corrupt or steal data. Security is needed to protect intellectual property such as proprietary algorithms that could reside on a wearable device. Secure authentication prevents device cloning and offers counterfeit protection for peripherals [21]. The systems of wearable technology should provide less invasive technology, but with the highest possible safety and security standards for all project stakeholders while at work [77].

4.2.11. Data processing and transmission

This layer of the wearable system involves processing tools needed to analyze the data generated by the hardware sensors. This data generated may need to be processed in a variety of stages depending on the metrics collected. Additionally, several stages or levels of data processing may occur before the processed information gets to the end-user with some localized (i.e. close to the hardware) while others may involve further processing after being transmitted to the Internet [63]. Thus, this layer or platform also provides interfaces for information exchange to and from the wearable device.

The simplest form of data processing will be in the proximity detection system in which the sensors may need to just detect hazardous materials, chemicals, or equipment and simply alert workers. A more complex processing will be one that can also distinguish the type of hazard detected so that it can be relayed to the worker with another layer within the system. Other forms of processing such as those for location tracking and physiological monitoring may also involve non-localized processing which occurs after the data has been transmitted to the Internet. The data transmission process may use any of the available standard communication protocols including Wi-Fi, Bluetooth, ANT +, and ZigBee. Raw and processed data may also need to be transmitted through any of the protocols for storage in the cloud for easy accessibility.

4.3. Integrated wearable technology for construction safety performance monitoring

This study has identified that different kinds of wearable sensors and systems can be used to measure and monitor a wide variety of safety performance metrics. Some of these sensors can monitor more than one parameter while others are complementary. However, these systems or sensors still have certain limitations which may be difficult to control if, for instance, a system or sensor is used in isolation. The strengths and weaknesses of each of these wearable sensors or systems have been evaluated and the integration of two or more of these sensors or systems for multi-parameter monitoring is obviously a good way to achieve maximum benefits from these technologies.

Table 3 presents the wearable sensors and systems that can be used to measure and monitor safety performance metrics evaluated in this study. It illustrates how the sensors can be integrated for multi-sensor platforms and multi-parameter monitoring. The trend in wearable technology is moving toward multi-sensor platforms that incorporate several sensing elements. For example, the standard for the next-generation of personalized self-tracking products appears to be some mix of an accelerometer, GSR sensor, temperature sensor, and possibly heart rate sensor (from which heart rate variability may be calculated) [63]. Instead of placing a single type of sensor in multiple locations on the human body (i.e. single-modality multi-location) as seen in most wearable devices, multiple sensor types using a multi-modal sensor to

Table 3
Sensors and systems for personalized wearable technology.

Technologies/ sensors	Physiological monitoring	Environmental sensing	Proximity detection	Location tracking
Infrared	x	x	x	x
Magnetometer	x	x	x	x
Radar	x	x	x	x
RFID	x	x	x	x
Sonar	x	x	x	x
Bluetooth	x	x	x	
GPS		x	x	x
Accelerometer	x	x		
Gyroscope	x	x		
Ultrasound	x		x	
UWB			x	x
Wi-Fi		x		x
Capacitive sensor		x		
EKG/ECG	x			
EMG	x			
GSR	x			
Humidity sensor		x		
Light sensor		x		
Noise sensor		x		
Pressure sensor		x		
Temperature sensor		x		

collect data from a single body location (i.e. multi-modality single-location) can be used [95].

The rationale behind this idea is to select sensors that are complementary such that a wider range of activities can be recognized. For example, using an accelerometer and a gyroscope together can differentiate whether the person is walking forward or walking left/right while such a classification fails if accelerometers are used alone. Moreover, this multi-modal sensor could be incorporated into existing mobile devices such as mobile phones. Integrating sensors into devices people already carry is likely to be more appealing to users and achieve greater user acceptance.

Additionally, the benefits derived from the use of ANT + technology to achieve interoperability between different sensors can be taken advantage of in developing such multi-parameter monitoring wearable devices. As the wearable devices get smaller, they gain efficiency and become more powerful. The integration of several sensors in the design of wearable devices would create a holistic procedure for monitoring safety performance as it would reduce the number of safety gadgets the workers would have to use to monitor different parameters. As depicted in Table 3, infrared, magnetometer, radar, RFID, sonar, Bluetooth, and GPS rank high as wearable sensors or system with multi-parameter applications. Some of the findings of this study can be considered in developing prototypes of construction-specific wearable devices for personalized safety monitoring.

5. Conclusion

This paper provides a review of the applications of wearable technology for personalized construction safety monitoring and trending. A comprehensive evaluation of the features of wearable technology and the resulting safety metrics thought to be capable of predicting safety performance and management practices is presented. The review showed that a wide variety of wearable technologies is being used in other industries to enhance safety and productivity while few applications are observed in the construction industry.

Knowing that the various sectors where wearable technologies have been greatly applied are not a high risk industrial sector like construction, there is an urgent need to change the status quo in terms of the application of wearable technologies in construction. It is time construction stakeholders and professionals strongly embraced these emerging trends in technological development to drastically enhance safety performance. This review has identified potential applications of wearable devices for capturing and monitoring various metrics responsible for the common injuries and fatalities on construction sites. The review completed in this study indicates that the sensors and systems used in the existing wearable technologies applied in other industrial sectors can also be implemented to measure and monitor a wide variety of safety performance metrics in construction.

Per the findings of this review, a few of the sensors and systems used in commercially available wearable devices have certain strengths and weakness which can effectively managed by the constructive integration of two or more of the sensing systems to achieve complementary benefits. Also, wearables devices with multiple sensor types in which a multi-modal sensor can be used to collect data from a single body location (i.e. multi-modality single-location) have been suggested for use in construction. Technology developers should intensify efforts in working on ways to derive meaning from multiple sensors integrated into a wearable device, to give a holistic view of how the body is moving or performing across multiple devices and sensors. The findings of this study can be used to integrate different wearable sensors and systems that can be used to design construction-specific wearable devices. Prototypes developed can be tested for their effectiveness for personalized safety monitoring. Further research in this area could include: selection of candidate wearable devices from the commercially available ones that can be applied to construction; or developing prototypes for construction specific wearable devices based of the findings of this study and performing experimental testing to ascertain their effectiveness.

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