

REVIEW ARTICLE

# Anticipation, Recognition, Evaluation, and Control: How AI and Digitalization Are Going to Revolutionize Health and Safety at Work?

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## ABSTRACT

**Background:** Occupational Health and Safety deals with hazards in the workplace through Anticipation, Recognition, Evaluation, and Control (AREC). Modern workplaces are given considerable digital makeovers, trying to integrate AI, IoT, robotics, and VR/AR, which from a wide perspective really distort OHS approaches in their being. These technologies put forth expectations of miraculous improvements but also pose newer risks.

**Methods:** A narrative review was conducted to systematically examine the changes brought by AI and digitalization to the OHS missions. Searches were made through PubMed, Scopus and the Web of Science, while Google was also used to retrieve organizational reports. Information was grouped and analyzed within the AREC framework, detailing the newest achievements as well as challenges.

**Results:** Exoskeletons prevent musculoskeletal injuries; UAVs inspect inaccessible areas; IoT enables real-time monitoring; VR/AR offers immersive training and hazard recognition; AI and robots predict hazards and automate dangerous tasks; and advanced technologies improve OHS across AREC. However, in addition to new physical risks from human-machine interaction, this adoption brings with it cybersecurity threats, data privacy issues, the possibility of job displacement, the risk that an over-reliance on technology will erode human skills, and complex ethical implications.

**Conclusion:** In conclusion, digitalization has revolutionary OHS benefits, but it also necessitates a worker-centered, ethical, and balanced approach. Companies need to make training investments, make sure that data is used ethically, conduct in-depth risk assessments, and promote ongoing development. To guarantee safe, and efficient technology integration, policymakers and researchers play a critical role in revising laws, creating ethical frameworks, and examining long-term impacts.

**KEYWORDS:** Occupational Health and Safety; Digitalization; AI; Risk Assessment; Risk Management

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## INTRODUCTION

The mission of occupational health and safety (OHS) is to address all forms of workplace hazards through Anticipation, Recognition, Evaluation, and Control (AREC). Workplace hazards can be categorized into several types, each posing unique risks to employees' health and safety [1]. Physical hazards include noise, extreme temperatures, radiation, and vibration, whereas chemical hazards include exposure to harmful substances such as toxic gases, solvents, pesticides, etc. On the other hand, biological hazards include risks from bacteria, viruses, fungi, and other microorganisms, while psychosocial hazards include workplace stress, bullying, harassment, and excessive workload that affect mental health and well-being. Safety hazards include slips, trips, falls, machinery malfunctions, electrical hazards, and other risks that can cause immediate physical injuries, and ergonomic hazards i.e workplace conditions that strain the body due to poor posture, repetitive movements, or improper workstation setup, leading to musculoskeletal disorders (MSDs), etc [2, 3].

To systematically manage these hazards, OHS professionals follow a structured approach, named AREC. Anticipation: Identifying potential hazards before they materialize, often through predictive analyses. Recognition: Detecting existing hazards in the workplace through inspections, employee reports, and incident investigations. Evaluation: Assessing the severity and likelihood of harm from identified hazards using qualitative and quantitative risk analysis methods. Control: Implementing measures to eliminate or minimize risks, such as engineering controls (e.g., ventilation systems), administrative controls (e.g., training and policies), and personal protective equipment (PPE) [1, 4].

Modern workplaces are undergoing a significant transformation driven by digitalization, characterized by the pervasive adoption of information and communication technology (ICT) [5]. This digital revolution encompasses a convergence of advanced technologies (AT), including artificial intelligence (AI), the Internet of Things (IoT), big data analytics, cyber-physical systems, and cloud computing, fundamentally reshaping organizational structures and operational processes. Unlike previous industrial revolutions focused on mechanization and automation of physical tasks, this era integrates these technologies into interconnected systems that enhance overall efficiency, productivity, and informed decision-making [6, 7].

These technologies can have significant impacts on occupational health and safety, both directly and through changes to work processes [8]. Key technologies at the forefront of this transformation in OHS include advanced robotics, AI and machine learning (ML), exoskeletons, unmanned aerial vehicles (UAVs), IoT, and virtual and augmented reality (VR/AR) [9]. These technologies hold the potential to revolutionize the way OHS is approached, offering innovative solutions for preventing workplace injuries and illnesses. However, the adoption of these powerful tools also introduces new risks that necessitate careful consideration and proactive management [8, 10].

This review is going to explore the general impact of digitalization on OHS, followed by a detailed examination of the role of each of the aforementioned technologies within the four core missions of OHS. Finally, it will address the potential new job risks and safety challenges that may arise from the increasing adoption of these technologies and digitalization in general.

## MATERIALS AND METHODS

This is a narrative review conducted to examine the impact of artificial intelligence and digitalization on core occupational health and safety missions. For this purpose, searches were conducted on the PubMed, Scopus, and Web of Science databases. Google search engine was also used to access reports and documents from involved organizations such as the International Labor Organization and the World Health Organization related to this issue. The keywords "occupational health", "industrial health", "artificial intelligence", "digitization", "machine learning", "robotics", "occupational health and safety", "exoskeleton", "wearable robotics", "unmanned aerial vehicles", "virtual and augmented reality", and "internet of things" were used for the search.

Then, the information obtained from this search was categorized and examined in 4 sections (Anticipation, Recognition, Evaluation and Control). The impact of digitalization and emerging technologies on each of these sectors was examined, and the latest achievements in these fields were reported.

## RESULTS AND DISCUSSION

### *Benefits*

#### *Anticipation*

Anticipation is based on acquiring and analyzing accurate and comprehensive data from the work environment. Therefore, technologies that can assist

in obtaining and analyzing such data may enhance the ability of occupational health professionals to anticipate potential hazards.

*Machine learning* algorithms excel in analyzing vast datasets, including historical accident reports, near-miss incidents, and various environmental factors. Now, the subtle patterns that they can pick out can help them predict hazards accurately before these get established. For example, an AI may analyze past history to find areas in a facility that are vulnerable to accidents due to reoccurring unsafe patterns and thus intervene appropriately to ensure these unsafe behaviors are addressed [11]. Real-time safety data can also be monitored using AI-based technologies to identify newly observed hazards so that corrective actions to terminate incidents can be taken immediately. Predicting such hazards can also analyze sensor data from equipment, predicting their possible failure and thus conducting maintenance on time to avoid accidents from equipment failure. In this way, the predictive nature of the tool uplifts occupational safety and health (OHS) from an after-the-fact approach to a scientifically forecasted approach that aims to prevent workplace incidents [12].

*Unmanned aerial vehicles (UAVs)* are transforming the way teams anticipate hazards on sprawling or remote worksites by using aerial inspections done before operations start. These flights scan the area from above, revealing hazards hidden from the ground. The UAVs sweep across the site, spotting unsafe conditions that a narrow ground view could miss, and delivering a detailed, bird's-eye view that feeds into smarter, preemptive safety plans [13]. The height they reach gives safety teams a complete view, while sophisticated imaging—like thermal sensors and 3D mapping—reveals dangers the human eye would overlook, including overheating equipment and subtle shifts in structure. With this early visibility, teams can act before problems escalate, putting preventive controls in place and enhancing overall safety [14].

*IoT* devices and sensors are crucial for anticipating potential hazards by continuously monitoring environmental conditions, equipment status, and workers' physiological data. IoT devices and sensors are very important to assess hazards by watching environmental conditions, the status of equipment, and physiological data of the workers. These active IoT sensors may monitor important stuff such as temperature, air quality, humidity, or sound in the environment. A wearable IoT device can keep track of

worker activity and warn workers if they are entering hazardous zones or near moving equipment [15]. Predictive maintenance systems use IoT sensors to identify early signs of wear or detect chance anomalies in equipment performance so that these can be maintained in time, thereby averting accidents. Also, wearable sensors, integrated into clothing or into accessories, monitor workers' vital signs continuously, including heart rate, body temperature, fatigue level, and blood oxygen saturation, giving early signals to the rise of health risks, like heat stress, or overexertion. The uninterrupted data streams flowing in from these IoT devices make it possible for trends and anomalies to be marked that could bring about alarm indications for potential hazards, so proactive interventions can be taken [16].

*Virtual Reality (VR) and Augmented Reality (AR)* technologies are increasingly deployed to enhance hazard anticipation through immersive safety training and interactive hazard-recognition exercises. VR affords a highly controlled, risk-free setting within which personnel can safely encounter high-risk operations—such as elevated work and the manipulation of heavy machinery—without exposure to actual danger. These virtual environments can faithfully replicate a spectrum of hazardous conditions, including toxic fume release, inclement weather, and the potential for collision with mobile plant [17]. VR-enabled hazard-recognition instruction encourages users to navigate interactive, virtual workplaces, thereby refining their spatial awareness and visual-object-recognition competencies that are essential for the detection of hazards in the physical environment. For example, immersive “risk hunts” on digitally reproduced construction sites guide operatives in identifying, analyzing, and anticipating sites of danger, thereby contributing to a measurable decline in incident rates. The cognitive skills fostered by such immersive exposure equip trainees to transfer hazard-identification competencies from the virtual to the physical realm with greater accuracy and confidence [18].

### *Recognition*

*Robotic systems* exhibit superior capabilities in detecting unsafe conditions and hazardous material, often better than humans in speed and accuracy. In unsafe environments, robots can detect gas leaks or toxic vapors; these robots measure air quality with little to no human intervention and provide the employer with critical data to act immediately. Many other innovative

robotic solutions exist to assist in the safety of your workforce: smart boots with sensors and AI algorithms will alert human resources to unsafe conditions like slippery surfaces or unexpected obstacles on a worker's pathway; smart helmets that combine several sensors can alert users to hazardous gases or pollutants within the air once the smart helmet itself is a potential hazard [19]. Autonomous mobile robots (AMRs) are rapidly being adopted for visual inspections—given the flexible construction of workspaces, these robots allow humans to identify a wide range of hazards that normally would be overlooked. Combining various sensor technologies into robotic systems will allow the detection of hazards that are outside our sensory detection, further enhancing your safety systems [20].

*Artificial intelligence (AI) and machine learning (ML)* improve recognition of unsafe behaviors, equipment failure, and dangerous situations with intelligent analysis of image and sensor data. There are AI systems that, through computer vision enablement, can do live video analysis of work locations and automatically recognize unsafe practices, such as the use of hazardous materials, or not wearing personal protective equipment (PPE). In addition to recognizing behaviors, AI can also identify equipment failure or other dangerous conditions and situations by recognizing patterns in the image and video data [21]. Additionally, AI algorithms automatically analyze data collected continuously by sensors and cameras allowing analysis of unsafe environmental conditions or unsafe practices and other deviations from standard operating procedures in real time. AI systems can also be trained to recognize still images, situations, or objects relevant to safety incidents and provide ideal context for risk assessment and response. Overall, automated monitoring can provide the most comprehensive and consistent identification of hazards and breaches of safety protocols compared to traditional manual methods [22].

Some advanced *exoskeletons* feature sensors capable of detecting when workers experience physical strain and delivering direct feedback to limit overexertion. Smart exoskeletons support workers in becoming more aware of when they are approaching or exceeding their physical limitations when performing their task. More advanced configurations contain sensors monitoring the force exerted which provides real-time feedback via haptic feedback or visual means. This feedback in the form of alerts, helps guide proper lifting techniques and minimize the physical strain on the worker [23]. Adaptive exoskeletons form an even more significant

advancement, as the support of the exoskeleton can automate and change based on the weight detected through integrated sensors or task load demands. In addition to the above example, integrating wearable sensors can allow the exoskeleton system to use the individual movement data from each worker's own exoskeleton to establish and analyze personal safety protocols and provide feedback based on each worker's unique biomechanics and working habits. Overall, real-time feedback loop on physical strain allows workers to make immediate adjustments to their movements and work practices therefore lessening the likelihood of injury [23, 24].

*Unmanned aerial vehicles (UAVs)* have a unique capacity to recognize unsafe conditions or structural weaknesses in dangerous conditions and provide information on potential hazards to facilitate workplace safety. UAV applications include recognizing a very wide scope of hazards (or potential structural weaknesses) in contexts unsafe for human inspection. In the construction sector, UAVs routinely inspect building sites and make assessments regarding structural integrity of existing buildings, bridges and other infrastructure [25]. UAV applications also include identifying specific hazards in real-time, such as workers not wearing specialized personal protective equipment (PPE), or improperly stored building materials. Some UAVs are even capable of carrying sensors, such as gas detectors, that allow for identification of hazardous materials, such as when industrial facilities have methane leaks. Since UAVs have the capability to use a variety of sensor technology and types to inventory danger or structural issues, rather than only visual observations, UAV applications allow for a fuller environmental/structural assessment [26].

*IoT* devices and sensors can alert workers immediately when unsafe situations, near misses, or violations of safety protocols are encountered by triggering immediate alerts and notifications. IoT devices can also be programmed to initiate automatic alerts when certain safety thresholds are exceeded, i.e., when temperatures go above a particular level or there is the presence of hazardous gases. Devices such as motion sensors placed in work facilities can also automatically detect and recognize deviations such as unauthorized movements in restricted spaces or work areas marked dangerous and can alert personnel [21]. Wearable IoT devices with fall detection technology can trigger alerts to supervisors and/or emergency responders in the event of worker falls or incapacitation.

Advanced security systems with IoT devices allow for smart video cameras with facial recognition and event detection, potentially recognizing unauthorized personnel or certain types of safety-related events. The potential of IoT systems to provide real-time alerts and notifications protects against an unsafe situation escalating by providing immediate alerts to unsafe conditions [27].

*Virtual Reality (VR) and Augmented Reality (AR)* technologies are central to predicting potential hazards, primarily through realistic safety training simulations and hazard identification exercises. By providing a safe and controlled environment in which employees can create a hazardous situation (e.g., working at heights, or operating dangerous equipment) VR's possibility for realistic hazard awareness and identification training is very helpful [28]. Simulations produced in VR can depict different types of dangerous situations that may include: fumes, gases, inclement weather and vehicle movements which might involve construction equipment colliding with construction workers. VR-based hazard identification training makes use of immersive virtual workspaces and engages learners in cases more so than around traditional forms of training where learners do little more than passive role play or following step by step instructions [29]. VR-based hazard awareness and identification training promotes spatial awareness and visual object recognition skills that are fundamental to recognizing real-life dangers. Using the example of using 'risk hunts' on virtual construction work sites, this learning experience will enable workers to recognize, associate and predict potential risks in real-time situations resulting in a decrease in workplace injuries. As VR immerses learners in hazardous virtual experiences, it promotes the cognitive skills required in predicting potential hazards, thus identifying danger in real life situations [28].

*Augmented Reality (AR)* enables workers to recognize hazards in an actual environment by adding information or visually marking hazards directly in their field of view. AR enables systems and applications to digitally overlay information such as safety guides, hazard warnings, or maintenance notices for a given piece of equipment in the worker's environmental context [30]. For example, an AR headset actively teaches employees what to avoid by placing a virtual hazard sign in the line of sight of the head-up display, while giving them the ability to actively work on the job site. In maintenance activities, AR can place a visual indication of danger on equipment or structural components so immediate disengagement

is more apparent. AR improves the worker's ability to identify potential hazards that require immediate attention assuming the context allows this awareness to occur [31].

### *Evaluation*

*Advanced robotics* technologies are extremely valuable for assessing the severity and extent of risk of specific incidents, particularly in hazardous or otherwise physically inaccessible environments. For example, construction companies are beginning to use drones to inspect hazardous areas, using aerial perspectives and can assess risk in situations that would otherwise represent a significant risk to human personnel [32]. Remote-control robots can provide new perspectives and injection sites for Biowaste. Autonomously mobile robots, with their scanning technologies like LiDAR and thermal cameras, enable comprehensive inspections of industrial facilities to evaluate structural safety and risk. Robots equipped with standard cameras and imaging technologies can also evaluate infrastructure condition in the utilities sector, which supports assessments of hazard, and impacts the risk-based prioritization of any repairs required. The ability to conduct remote hazard assessments has significant implications for construction and evaluation in hazardous settings, especially in the post-incident phase or where risk is related to structural stability [33].

*Artificial intelligence (AI) and machine learning (ML)* are powerful means of evaluating safety intervention effectiveness and predicting likelihood of future events based on audited data. AI can measure numerous safety metrics, key performance indicators (KPIs), and all results to provide leadership with a roadmap of possibilities for improving safety culture; thus, establishing a safety intervention framework based on real data [33]. Additionally, AI will triage incident reports based on severity, causation, and impact, allowing environmental, health, and safety (EHS) professionals to assess workplace safety comprehensively and identify opportunities for improvements. Moreover, AI can quickly assess historical data on previous safety interventions and identify if they have been successful in reducing incidents and improving safety outcomes [34]. AI with Predictive Analytics will evaluate the likelihood of future incidents based on the trends and patterns that emerge from the analyzed data to help organizations understand and anticipate risks to the safety of their people. This evaluative ability also provides organizations with a tool for continuous improvement

in OHS programs through the ongoing assessment of real-world data, but to proactively mitigate definitions of safety as they emerge [35].

*Exoskeletons* provide powerful tools to analyze the physical demands associated with job-related tasks and assess the success of ergonomic interventions. Exoskeletons are generally equipped with sensors that measure the forces and torques exerted by workers during strenuous activities such as lifting, pushing and pulling others. Motion capture technology embedded in exoskeletons records worker movements such as joint angles, velocity and acceleration [23]. This can provide important information regarding awkward posture and repetition – two key indicators of increased ergonomic risk. The data collected by an exoskeleton when performing a task can be ported into specialized ergonomic analysis software to produce detailed reports on the aspects of the tasks that present possible risks based on established guidelines [36]. Additionally, exoskeletons can objectively assess the level of muscle activity and joint loading reduction in muscular junctions of interest when using an exoskeleton for certain tasks as a way to assess its effectiveness and success as an ergonomic intervention. Providing standardized economic data points of physical demands and the ability to assess intervention effectiveness could provide a better understanding to practitioners and researchers working to improve workplace ergonomics [37].

*Unmanned aerial vehicles (UAVs)* provide a rapid and efficient method to evaluate damage following workplace incidents or assess hazards in locations that people cannot physically access. After an incident, UAVs can be dispatched in a timely manner to map the incident area and develop an overall damage profile. UAVs always offer unique advantages for evaluating hazards in locations where it is too physically dangerous or impossible to assess them without putting layperson or responder safety at risk [13]. UAVs can collect a large quantity of visual and thermal data for hazarded locations difficult to access, or too costly or dangerous to reach, from sustained heights (mounting heights) or unstable structures. UAVs also offer a unique opportunity to map disaster incident locations and identify potentially safe points of access for responders and other first responders. The speed of UAVs, and most notably their ability to provide remote evaluation, represents an emerging and arguably incomparable solution in developing and conducting post incident evaluations of potentially high hazard locations or locations that are otherwise inaccessible [38].

With *IoT technologies*, it is possible to evaluate worker's exposure levels to various hazards – and the effectiveness of the control measures in place- in real-time, and rely on data to inform future health hazard exposures. Environmental sensors within the workplace can collect real-time data regarding exposure levels to harmful gases, airborne contaminants and excessive noise on behalf of workers. This is useful for risk assessments as well as compliance. Wearable IoT devices could monitor individual exposure to hazardous materials or the duration of exposure to high noise levels. Thus, reporting actual exposure data for targeted action [39]. Safety-related data is generated and automatically recorded and securely stored right through the IoT systems. The data recorded can later be analyzed to find trends in worker exposure and the effectiveness of existing control measures, while also supporting the development of better safety protocols. Collecting, analyzing, and reporting the safety-related exposures data provides an organization with information about its safety performance, trends to improve, and data-informed recommendations to minimize exposures [40].

*Virtual Reality (VR)* technology offers a unique means of assessing worker performance in safety-critical tasks and their understanding of complex safety processes in a controlled and measurable way. VR training thick with measurable results provides a sense of how well an employee is performing their duties by measuring established performance points of time taken to complete a task, error rates and or failure to comply with key safety aspects. In businesses and industries where rigid compliance is crucial (e.g. emergency response, aviation, marine inspection), VR captures an accurate representation of what a worker would respond like in the event of critical events such as fire, chemical leaks or life-altering medical procedures [41]. VR can assess how well a worker can identify hazards and risks, utilize protective equipment and act upon situations that present themselves in the training simulations. In such reports that can synthesise and compare the performance aspects of a participant along with using AI (artificial intelligence) embedded within the VR training platform, possible analytics that can highlight their capabilities and individual aspects that may require more training or continued reinforcement. The advantages of measurable performance and decision making assessments in virtual scenarios without any risk exposure provide employers with a view of their workforces readiness for real-world safety issues [38, 41].

### Control

*Advanced robotics* plays a critical role in hazard mitigation by taking on jobs that are dangerous for humans to do or providing safety in dangerous situations. In factories, robots are particularly suited for taking over the repetitive, boring tasks, that ultimately lead to fatigue and mistakes. As a prime example, autonomous vehicles in factories have shown a significant reduction in accident rates [42]. Robots can also work with toxic substances, or be placed in extreme temperatures, thus minimizing human exposure to that danger. Most collaborative robots (cobots) work alongside humans, where there is safe, yet unsafe, highly-repetitive jobs, or physically unsafe, enabling human workers to move on to work of greater value. In manufacturing and logistics, cobots and robotic arms can take over tasks like machine tending, assembling products, machine inspection, and safely automate dangerous jobs that decrease the need for direct human exposure to machines in a potentially hazardous working environment. This direct replacement of human labour to work with dangerous tasks is one of the most important ways that robotics can improve worker health and safety [43].

*Artificial intelligence (AI) and machine learning (ML)* can assist organizations in managing and controlling risks, including providing on-the-spot alerts to workers or management, automating safety protocols, and optimizing work processes with safety in mind. For example, a robust AI-enabled safety management solution may help prevent accidents and injuries by promptly warning employees (and management) of possible risks [44]. In more sophisticated scenarios, an AI-enabled robot could take action, like immediately shutting down defective machinery to mitigate risk. AI can also automate incident management, which can include data collection, detailed analysis, and comprehensive reporting. Furthermore, AI can support organizations in maintaining risk safety compliance with complex regulations by automating continuous monitoring and reporting. By analyzing risk data and spotting hazards, AI contributes to risk managing and optimizing work processes by fully integrating safety into work processes. Thus, AI and ML provide active, often real-time, risk management and control, a significant risk management strategy for preventing workplace accidents and injuries [33].

*Exoskeletons*, as an emerging form of workplace safety, address physical hazards due to their ability to enhance worker strength and greatly reduce

physical stress from strenuous tasks in the workplace. Exoskeletons enhance the worker's natural strength allowing them to safely move heavier loads. Moreover, the external support delivered by the exoskeleton greatly reduces the need for repetitively conducted motions, which often cause musculoskeletal disorders [45]. Within the field of material handling, exoskeletons have been shown to lessen manual lifting thereby reducing the risk of debilitating back injuries. Exoskeletons also provide direct physical support during tasks that involve repeated strains, perhaps even mitigating some of the work-related musculoskeletal pain and injuries experienced by workers. The potential for strength augmentation while simultaneously decreasing the strain on the worker through the use of exoskeletons directly moderates the risk of physical injuries related to heavy lifting, awkward postures, and repetitive movements in various occupational contexts [46].

*Unmanned aerial vehicles (UAVs)* can assist with hazard management in the workplace in several ways. For example, they can carry essential safety items to remote locations or to workers during a sudden emergency, and they can help remote observers monitor for compliance with acceptable safety procedures [13]. When workers need safety equipment and must have it immediately, because access is restricted (confined spaces) or because work is taking place on uneven surfaces at significant heights, UAVs can deliver respiratory protection, first-aid kits, or communications equipment directly to the worker. UAVs equipped with high-definition cameras can be used to monitor work conditions and activities from aerial views that safety personnel can use to watch worker job task compliance instead of trying to watch it from the ground. For example, safety personnel can use UAV's aerial views to monitor if a worker is using proper fall protection works, or if they are using proper PPE when conducting tasks [14]. In many applications, UAVs can provide real-time relay of an observation to workers from onboard communication systems to remind workers of procedures or to warn them of unsafe conditions or hazards within proximity. And in a few industries, UAVs can also be used to control the vehicle or pedestrian traffic through hazardous work zones to ensure safe movement of personnel and equipment within operational zones. The remote delivery of equipment and monitoring compliance adds an important level of control for preventing or reducing workplace hazard exposure [47].

*IoT* devices and sensors can actively mitigate workplace hazards in a variety of ways, ranging from triggering alarms, programming environmental control

systems, and generating personalized and adaptable safety information for workers. When IoT sensors detect hazards, the system can automatically trigger audible and visual alarms to alert workers in proximity. In workplaces with automated environmental controls, IoT sensors that control variables such as air quality and temperature can subsequently control ventilation, heating, or cooling systems to maintain safe and comfortable conditions [48]. Wearable IoT devices that monitor workers' physiological data can provide real-time individual safety recommendations, for example, the device could prompt workers to take a break if the sensor detects fatigue or the onset of overheating. IoT sensors can also be associated with access control systems to restrict access to hazardous areas to only authorized personnel. Because IoT systems can interact with the physical workplace environment and provide real-time advice and feedback, their capability to actively mitigate risks is immediate [49].

Controlled Risks through *Augmented Reality (AR)* technology that can safely guide workers through complex or dangerous tasks and even provide access to an expert based remotely. AR technology is an effective risk management tool because it can project the correct

procedural steps and real-time instructions directly into the worker's field of view of the task. This means that a worker in an AR system adheres to critical safety protocols as correctly as possible and maintains an accurate and detailed way to do it. Moreover, AR technology allows a worker hands-free, on demand access to information, but allows them to learn and perform the task in a safe manner without being familiar with the task [28]. In some instances, there could be a need for specialized knowledge to proceed; AR can support collaboration, by allowing remote off-site support personnel share the worker's field of view (through the AR enabled device) to provide visual and audio guidance, in real-time. For some larger or complex tasks, such as conducting equipment maintenance or emergency repairs, AR can provide step-by-step instructions with detail to ensure all the substantial tasks in each step be done correctly and safely. The risk of errors and accidents minimized significantly with the just-in-time information and remote support provided by AR during longer, more complicated, or dangerous procedures [28, 50].

Table 1 summarizes the role of each of the discussed technologies in the four core missions of occupational health and safety (OHS).

**Table 1.** A summary of the role of emerging technologies in the four core missions of OHS

Technologies	OHS Missions			
	Anticipation	Recognition	Evaluation	Control
Advanced robotics	-	-	-	Perform hazardous tasks
AI/ML	Predicting potential safety risks, process vast amounts of data to identify patterns and predict future events	Real-time hazard detection	Automating incident reporting, automated monitoring and report generation	Providing on-the-spot alerts to workers or management, automating safety protocols, and optimizing work processes with safety in mind
Exoskeletons	-	-	-	Assist physical activity, providing direct physical support to workers in physically demanding jobs
UAVs or Drones	Collect valuable data	Inspecting difficult or dangerous areas inaccessible to humans	Providing comprehensive overviews of safety conditions	Deliver essential safety equipment
IoT	Collects and exchanges real-time data	Continuous monitoring and management of workplace conditions	Real-time data collecting with environmental sensors	Automated safety alerts, remote access control to dangerous areas
VR/AR	Creating realistic and controllable environments for safety training, simulate real-world scenarios	Enabling visualization of potential dangers in both simulated and real-world settings, simulate real-world scenarios	Simulate real-world scenarios	Creating realistic and controllable environments for safety training, emergency preparedness training, offer step-by-step guidance for complex or hazardous tasks, remote expert assistance

### *Challenges and Risks*

Digitalization along with advanced workplace technologies provide multiple advantages for occupational health and safety but generate new risks that need active management.

#### *Cybersecurity Threats and Data Privacy Concerns*

OHS depends on digital systems and interconnected devices which create increased cybersecurity risks that can interrupt operations while exposing confidential information to hackers. Worker data collection and analysis through digital tools including wearables and monitoring systems presents important privacy concerns together with risks of information exploitation. The organization needs to implement strong security measures to protect sensitive data from unauthorized access while following all data protection laws [51]. Organizations that fail to manage these risks effectively will experience data breaches together with financial penalties and legal action and workforce trust will suffer. The networked design of digital systems creates security weaknesses that hackers can exploit while collecting personal information which generates ethical and legal privacy concerns. Organizations need to adopt a proactive workforce development strategy that provides workers with modern digital skills to meet the changing nature of work [52].

#### *Potential for Job Displacement and the Need for New Skills and Training*

The automation of different tasks using advanced robotics and AI/ML systems creates a possibility of employment reduction in particular fields which generates worries among employees. Workers must obtain new competencies about these technologies by learning how to supervise automated systems and perform data analysis and use AI-driven tools effectively [53]. Workers require training on contemporary technologies to enhance their ability to prevent and handle occupational hazards in changing workplaces. The fast technological development demands ongoing education and professional development programs to maintain worker competencies at current levels of relevance. Digital work transformations demand active workforce development strategies which enable employees to acquire necessary digital skills [54].

#### *Potential for Over-Reliance on Technology and the Erosion of Human Skills*

While technology can greatly improve safety and make work more efficient, relying too much on

these tools without enough human involvement can have downsides. Workers may start to lose some of their critical thinking and problem-solving skills if they depend solely on technology to make decisions. Additionally, when digital tools are used to closely monitor employees, it can create stress and reduce trust in the workplace [55]. That's why it's so important to find a healthy balance. AI and other advanced systems should be there to support workers, not replace their role in important decisions and day-to-day tasks. When introducing new technologies to occupational health and safety, organizations should put people first—making sure the tools suit the needs and strengths of the workers who use them. Ultimately, technology should help people do their jobs better, but human experience and judgment are still essential, especially when it comes to keeping workplaces safe [56].

#### *Ethical Implications of Using These Technologies in OHS*

As more advanced technologies become part of workplace safety and health, it's important to think carefully about the ethical challenges they bring [57]. For instance, when AI systems are used to evaluate how people perform at work or make decisions that could affect someone's job, there's a real need to ensure these decisions are fair, transparent, and easy to understand. If the data used to train these systems reflect existing biases or inequalities, those same problems can end up baked into the technology, leading to discrimination. There are also concerns about how companies collect, use, and store workers' personal data, especially when digital tools make it possible to monitor so much about what employees do [58]. This kind of constant monitoring can lead to new stresses, leaving people feeling watched all the time or like they have less control over their work. To protect workers and use technology in a responsible way, ethical questions should always be at the center of decisions about which tools to adopt and how to use them. The goal should always be to support and safeguard people—not unintentionally put them at risk [59].

#### *Other Emerging Risks*

As advanced technologies become a regular part of our workplaces, they bring new kinds of safety challenges that need special attention. For example, if people and robots don't interact properly—especially when they work side by side—there's a real possibility for accidents or injuries [60]. Spending long hours using robotic control systems or staring at monitoring

screens can also lead to new physical issues, like muscle strain or eye fatigue [61]. Some of these advanced machines, like robots with lasers or those that produce electromagnetic fields, introduce unfamiliar hazards that workers might not expect. Drones (or UAVs) are another example: when they're used around people working at heights, they can be distracting, which may increase the risk of falls [62]. There's also a chance that workers might depend too much on wearable technology like exoskeletons, possibly taking more risks because they feel fully protected [63]. As these technologies become more common, it's important to recognize and proactively manage the risks that come from working closely with machines. Making sure people know how to use these tools safely—and understanding the potential pitfalls—will be key to keeping workplaces safe [64].

## CONCLUSION

Digitalization and advanced technologies are transforming occupational health and safety (OHS), offering tools like robots, AI, exoskeletons, and immersive training to improve workplace safety and health. While these innovations hold great promise for hazard management, their adoption requires a balanced and ethical approach, weighing benefits against potential risks to workers. To maximize the advantages and minimize the dangers, organizations should create comprehensive, worker-centered strategies for technology integration. This involves investing in training and upskilling, ensuring ethical use of technology and data, conducting thorough risk assessments, and fostering continuous improvement in OHS practices. Policymakers play a vital role by updating regulations, establishing ethical and legal frameworks, supporting research, and encouraging collaboration among stakeholders. Meanwhile, researchers should investigate the long-term effects of these technologies, assess their effectiveness in diverse settings, explore ethical challenges, and develop ergonomic guidelines to ensure safe and effective OHS technology design and use.

### Conflict of Interest

The authors declare no conflict of interest.

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### Author's Contributions

Study Conception or Design: N Mehrparvar

Data Acquisition: N Mehrparvar

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Manuscript Drafting: S Omari Shekaftik, N Mehrparvar

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All authors have approved the final manuscript and are responsible for all aspects of the work.

### AI Statement

During the preparation of this work the author(s) used Chatgpt in order to translate and rewrite some parts of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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The authors confirm that no AI tools or services were used during the preparation of this work.

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