Foundation

Global Safety Evidence Centre

The intersection of occupational safety and health with emerging technology: Scoping and mapping the evidence to plan for future research

Safe Work

Evidence Review

Technical Report

Preface

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The Lloyd's Register Foundation Global Safety Evidence Centre is a hub for anyone who needs to know 'what works' to make people safer. The Centre collates, creates and communicates the best available safety evidence from the Foundation, our partners and other sources on both the nature and scale of global safety challenges, and what works to address them. It works with partners to identify and fill gaps in the evidence, and to use the evidence for action.

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Lloyd's Register Foundation, 71 Fenchurch Street, London, EC3M 4BS, United Kingdom

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This report is authored by: **Hampton Toole, Emily Hutton, Kankan Zhang, Christy Wong, Pamina Smith, Giulia Maistrello, Nick Fahy and Madeline Nightingale**

Executive summary

This report presents the findings of a scoping evidence review on the impact of emerging technology on occupational safety and health (OSH), informed by a literature review and data collection with experts, including interviews and a workshop. As well as providing a summary of the evidence landscape, the review summarises findings for six technologies selected based on an initial literature search and feedback from experts: algorithmic management, emotional artificial intelligence (AI), wearable devices, OSH-focused smartphone applications, collaborative robots (cobots) and augmented and virtual reality (AR/VR). Our summary findings are as detailed below.

The evidence landscape on emerging technology and OSH remains patchy

The evidence base is limited and uneven across different technology areas, sectors and industries. Overall, there is a lack of rigorous research, with the evidence comprised predominantly of small-scale studies that lack a robust counterfactual. The evidence base is stronger in certain technology areas, for instance, safety-related smartphone applications and the use of AR/VR in OSH training. Other technologies may nonetheless have a more profound impact: for instance, forms of 'safetytech' (technologies implemented with improved safety as a primary outcome of interest) that eliminate or drastically reduce workers' exposure to OSH risks or technologies such as algorithmic management, emotional AI and cobots which have the potential to engender new ways of working.

Technologies are constantly changing and being applied in novel ways, making the landscape for evidence generation complex. Technologies may be implemented for reasons other than safety (such as productivity and efficiency), meaning that organisations are less likely to monitor and assess the impact on health and safety outcomes. Experts also noted barriers to information sharing, with employers sometimes reluctant to share data on the use and impact of new technologies due to commercial sensitivities.

Emerging technologies have impacts on occupational safety and health, although many of these are underexplored

Reflecting these limitations, it is difficult to draw firm conclusions about the impact of new technologies on OSH. Nonetheless, some overarching themes can be identified.

First, new technologies can have a profound impact on workers' safety and health even if they are not introduced with safety in mind. For example, wider technologies such as Algorithmic Management and Emotional AI may have substantial negative implications for workers, particularly when it comes to their exposure to psychosocial risks.

Second, whilst the evidence is uneven across different forms of safetytech, evidence supports the use of certain technologies such as smartphone applications and AR/VR within health and safety functions. For instance, there is robust evidence to support the use of safety-related smartphone applications to promote behaviour change and generate positive physical and mental health benefits for workers.

Third, the benefits of technology, and in particular safetytech, need to be balanced against potential risks, which are not well understood. For instance, forms of safetytech such as wearable devices could infringe on workers' privacy or place a greater burden on them to manage OSH risks. Safetytech could also contribute to complacency in addressing OSH risks in the workplace.

Directions for future research

This report highlights the need for additional research to understand existing demand for and use of emerging technologies in workplaces, and to understand how these technologies impact workers' safety and health. Regarding transformational technologies such as Algorithmic Management and Emotional AI, it is critical to understand their impact on workers' psychosocial risks, especially considering that these technologies are already widely adopted. Large-scale, real-world rigorous evidence is needed to better understand these impacts, which requires adequate incentives for stakeholders (including employers and technology developers) to participate in and contribute to research. For both safetytech and wider technologies, it is important to collect data on the unintentional or unanticipated OSH-related consequences of new technologies. Future work should also focus on bringing stakeholders together to share knowledge, data and best practice.

Contents

Abbreviations

AI	Artificial Intelligence
AR	Augmented Reality
CBT	Cognitive Behavioural Therapy
Cobots	Collaborative robots
EAI	Emotional Artificial Intelligence
EU	European Union
HSE	Health and Safety Executive
INT	Interview
IoT	Internet of Things
LLM	Large Language Model
MHealth	Mobile-Health
OSH	Occupational Safety and Health
RCT	Randomised Controlled Trial
RAG	Retrieval Augmented Generation
REA	Rapid Evidence Assessment
UK	United Kingdom
US	United States
VR	Virtual Reality
WS	Workshop

Figures, tables, and boxes

1. Introduction, research aims and methodology

RAND Europe has been supporting Lloyd's Register Foundation (hereafter The Foundation) in their plans to establish a Global Safety Evidence Centre (hereafter referred to as 'the Centre'). This initiative draws inspiration from the United Kingdom (UK)'s What Works networks, a government initiative designed to improve public services by promoting evidence-based decision-making. These centres focus on evaluating and disseminating research to inform policy and practice across various sectors, such as education, health, or policing. RAND Europe's feasibility study for the Centre highlighted that, in order to be successful and have impact, evidence centres need to focus on well-defined topics and priorities (Maistrello et al. 2023).

To aid The Foundation in selecting priorities for the Centre, RAND Europe conducted scoping evidence reviews on potential areas of interest, which emerged from stakeholder consultations during the feasibility study and were refined through further discussions with The Foundation. The present review examined the potential benefits and pitfalls of emerging technologies for occupational safety and health (OSH).

Simultaneous to this study, another research team conducted a separate review to support The Foundation's plans to establish the Centre, employing similar research methods. This parallel review focused on the impact of climate change on OSH in selected sectors[1].

1.1. Research aims

The report explores the interaction of emerging technologies and OSH, focusing on technologies that directly improve or affect worker health and safety. The primary aim of this review was to scope the extent of existing knowledge; evaluate the volume, nature and quality of available evidence and to identify the potential research gaps where the Centre could make an impact.

The research questions used to guide the research were as follows:

- How do emerging technologies influence workers' occupational safety and health? What are the key technologies and/or sectors?
- What is the nature of the available evidence on this topic? What are the gaps?
- How can a Global Safety Evidence Centre add value to this area?

1. Lloyd's Register Foundation, "The Impact of Climate Change on Safety at Work," Lloyd's Register Foundation, 2025. doi: 10.60743/H5GK-TQ84.

1.2. Methodology

This review was carried out in four steps:

1. A broad mapping of the academic literature on the topic, using innovative Artificial Intelligence (AI) tools.
2. Targeted reviews on specific technologies, using purposive searching and including grey literature to provide an overview of issues and evidence.
3. Expert input through individual interviews.
4. Workshop to review and refine our findings.

Each of these steps is detailed in the following paragraphs.

1.2.1. Broad mapping of the topic using innovative AI tools

The first phase of this review aimed to gather a broad understanding of the evidence landscape around emerging technologies and OSH. Given the vast amount of literature on this topic, we utilised two AI tools developed by RAND Europe to provide a broad mapping of the academic literature and identify key articles. These tools aimed to offer a high-level characterisation of the literature, in order to provide a basis for selecting areas of focus. While these tools helped to give us a sense of the literature as a whole, researchers remained essential to the process, thoroughly reviewing AI-generated outputs, analysing the information, organising the findings and drafting the report.

We began by conducting a literature search using the **OpenAlex database**, an open-source data catalogue that indexes over 240 million journal articles and updates daily. OpenAlex was selected for its breadth and compatibility with our AI tools, allowing us to efficiently integrate search results into our analysis workflow. The literature search on OpenAlex compiled a dataset containing metadata for each identified paper, including the full abstract, author information, and the publishing journal. The search string initially yielded about 1.2 million academic titles published in English between 2021 and 2024. We restricted the publications timeframe to three years due to the extensive volume of literature on this topic. These papers were ranked by relevance to the search terms, with the top 2,000 being selected for further analysis. The analysis of the metadata was conducted using two AI tools.

The first AI tool used was an **interactive topic clustering map**, which enabled us to visualise the thematic structure of the literature using the abstracts of all 2,000 selected papers and analyse research clusters at different levels of granularity. Once the clusters of related themes were identified, a large language model (**LLM**)[2] was employed to summarise each cluster, providing an overview of key topics across incrementally broader categories. This facilitated a deeper understanding of the thematic landscape and guided the next steps in our analysis. The map was designed for use at multiple

2. This was a RAND private implementation based on Microsoft's Azure OpenAI service using the GPT4 model.

levels: at level one, individual research papers were represented as distinct points, each linked to semantically related articles and displaying their title, authors, and abstract. At higher levels, each point corresponded to a thematic cluster, with a detailed description available by clicking on it.

The second tool, employing a **Retrieval Augmented Generation (RAG)** approach, functioned as a chatbot. Researchers used this tool to ask questions about the identified body of literature. The tool could retrieve information from the abstracts of the selected articles and cluster summaries, providing concise answers along with reliable references to specific articles.

Using these tools, we **refined the search terms** iteratively throughout this first phase of the research. We conducted three rounds of refinement, improving the specificity of the search by excluding topics that were not directly relevant to the research aims.

The final string used for bibliometric analysis is presented in Table 1.

Table 1. Final search string

"safety" AND ("Tech" OR "Digital" OR "Cyber" OR "AI" OR "Artificial intelligence" OR "Machine learning" OR "Deep learning" OR "Robot" OR "Autonomous" OR "comput" OR "nano" OR "quantum")

1.2.2. Technology-specific reviews

The aim of the next phase was to conduct targeted reviews on individual technologies pertinent to OSH to identify key themes and areas where further research is needed.

The research team firstly identified a long list of emerging technologies relevant to OSH. The team gathered information on key technologies identified from the bibliometric analysis (see section 1.2.1) and supplementary searches using adaptations of the search string in Table 1. Technologies were then shortlisted using four criteria (below), which were determined in consultation between RAND Europe and The Foundation.

1. **Volume of OSH-related evidence:** the volume of evidence on the technology and its implication to OSH should be sufficient to conduct an evidence synthesis and manageable within the time and resources available.
2. **Nature and quality [1] of OSH-related evidence:** the evidence base should include empirical studies of high enough quality to draw meaningful conclusions.
3. **Relevance and impact:** the technologies should be aligned with The Foundation's interests and priorities, with scope for impact from strengthening the evidence base on the topic.
4. **Added value:** the technology selected for the targeted reviews should be one where no recent evidence review with a similar scope has been conducted.

1. The methodological rigour of sources was assessed using the Maryland Scientific Methods Scale, as well as a qualitative summary of the limitations of each source.

The research team produced a long list of 17 topics and conducted a preliminary investigation into the nature, volume and quality of OSH-related evidence. From the long list, five technologies were originally selected to be the focused of targeted reviews based on the criteria above: algorithmic management, emotional artificial intelligence (AI), wearable devices, smartphone applications and collaborative robots (cobots). One additional topic - augmented and virtual reality – was moved from the longlist to the shortlist following the validation workshop (Section 1.2.4).

The topics that were not selected were as follows:

- AI-generated misinformation and disinformation
- Autonomous vehicles
- Smart cities
- The IoT and transport safety
- Smart education
- AI in medical screening and diagnosis
- Technology-facilitated domestic abuse/intimate partner violence
- Blockchain technologies: workplace applications
- Cyber-crime/organised crime
- Digital twins
- The metaverse

While they were not the focus of this report, they could be the focus of future research.

The research team then conducted separate searches for each of the shortlisted technologies to identify key academic articles and grey literature, complementing the academic sources identified in OpenAlex using the AI tools (Section 2.1). Searches were conducted on Google, Web of Science and Google Scholar, and other online bibliometric tools like Litmaps, Inciteful, Consensus, Co-Pilot, and Scispace. The team was encouraged to innovate and adapt the search strings to capture systematic reviews and relevant empirical evidence specific to each technology. The findings on each technology are presented in Section 2.

1.2.3. Expert Interviews

The research teams conducted stakeholder interviews to validate the findings and gain further insight from key informants. The interviews were semi-structured, lasted approximately 45 to 60 minutes, and were conducted via Microsoft Teams. Given the complexity of the evidence on each technology, the interviews provided unique perspective on these topics, often offering insight into specific contexts. The team conducted seven interviews with eight experts in OSH and technology from government/EU agencies or regulatory bodies (3 interviews), organisations supporting industry/OSH practitioners (2 interviews) and research consultancy organisations (2 interviews).

The interviews aimed to:

1. Understand perspectives on emerging technology and OSH which are otherwise not reflected in the academic and grey literature;
2. Understand practitioner views on the risks, benefits and challenges associated with emerging technologies in real-world settings; and
3. Ascertain any gaps in the research approach to date, including the selection of technology areas and the approach to evidence review.

We identified participants to interview in two ways:

1. Stakeholders within The Foundation and RAND Europe's networks, who we knew were working in the OSH and technology space; and
2. Lead authors of academic papers on OSH and emerging technology generally, as well as on OSH and specific technologies covered in this report.

1.2.4. Validation workshop

The team conducted a workshop (WS) with colleagues from The Foundation and Lloyd's Register (LR), as well as OSH experts within The Foundation and RAND Europe's networks. The workshop lasted 2h30min and was conducted virtually on Microsoft Teams. Excluding RAND Europe employees, twenty-two stakeholders attended the workshop on the 23rd September 2024. Among the attendees, about half were from The Foundation (nine) and LR (two), who used this opportunity to learn about the study's interim findings. The remaining participants were from national and international organisations specialising in OSH, with a particular interest and expertise in the interaction between technology and OSH. The purpose of the workshop was to gather stakeholder input on findings to date and identify further research needs in addition to those identified through the scoping evidence review.

During the session, the research teams presented interim findings from the topic reviews and facilitated discussions around key topics:

1. Evidence gaps: explored areas where current research is lacking or insufficient.
2. Impact opportunities for a Centre: discussed potential areas where a Centre could make a significant impact.
3. Completeness of the scoping review: evaluated whether any critical elements were missing from the review.
4. Ranking of technologies: an online voting focused on identifying which emerging technologies hold the most promise for OSH as well as how much evidence is available for each.

1.3. Strengths and limitations

The methods employed in this phase have strengths and limitations that reflect the exploratory nature of this scoping study.

Scoping exercise: The aim of this work was to produce an initial overview of the available evidence on the OSH implications of emerging technologies. Given the large body of literature on this subject and the rapidly evolving nature of the subject matter, this work is not exhaustive.

Stakeholder engagement: This report benefits from expert insights, but these are based on the participation of a relatively small number of individuals and may not be representative of wider views and opinions among OSH experts and practitioners. The study did not include direct engagement with employers or workers, whose perspectives are important in understanding the impact of new technologies on OSH. However, where possible, we summarise evidence based on research conducted with these groups.

Novel methodological approach: The research team used novel AI tools to enable efficient, high-level engagement with a large body of literature on emerging technology and OSH. Using this approach enabled the research team to review substantial quantities of information which would not have been possible using traditional approaches. However, these tools are novel, they do not critically appraise methodological robustness of the included studies and they still leave large scope for interpretation of the information they provide. Further research is needed to compare how the results generated by these tools are distinctive in comparison to other methods. Additionally, potential issues such as hallucinations and reference inaccuracies, often associated with AI, were mitigated by exclusively including articles within the OpenAlex database as the input for our AI tools for evidence mapping and clustering. Furthermore, any article suggested by these or any other AI tools, such as Inciteful, Consensus, Co-Pilot, was thoroughly reviewed by the research team before being included in the study.

Geography: While the research team did not specify any geographical scope to be prioritised, the majority of stakeholder engagement came from high-income countries, including the UK, EU, and New Zealand. This helped the research team to understand the evidence produced in these countries to a high degree, and the challenges associated with producing this evidence in these areas. The research team did not find substantial evidence from low- and middle-income countries, and it is assumed that there may be different challenges in these settings. Only research published in English was included in the review.

2. Findings

In a survey of almost 5,000 employees in the UK, a greater number of respondents reported that their exposure to health and safety risks at work had worsened, rather than improved, over the last three years due to technology (Soffia, Leiva-Granados, et al. 2024). This overall trend is likely to mask considerable variation according to the type of technology and/or OSH risk, as well as the individual workplace and worker. Not only can technology both promote and undermine OSH, but it does so in complex, multi-factorial ways that may differ from one context to another. Combined with the rapidly evolving nature of technology, this makes it a challenging area to collect and synthesise evidence to better understand these impacts. In this section, we present findings from a scoping review looking at the available evidence on the impact of emerging technology on OSH.

An 'emerging' technology has been defined as '*a radically novel and relatively fast-growing technology characterised by a certain degree of coherence persisting over time and with the potential to exert a considerable impact*' (Rotolo, Hicks, and Martin 2015). For the purposes of this scoping review, we also consider technologies that may be more established (i.e., not 'emerging' technologies) but have been applied in new or innovative ways in a workplace context, something noted by stakeholders as a key component of innovation. An example of this is the use of smartphone technology to develop OSH-related applications for use in the workplace context. For this scoping review we focused on the interaction of emerging technologies and OSH, which encompasses both physical and psychosocial risks[1].

2.1. Overview of the findings

Drawing on the academic and grey literature, interviews and workshop, this section outlines key themes and overarching findings for the scoping review. Altogether, we find that **there are a wide range of technologies used to improve OSH outcomes, but these may have unintended impacts on workers' physical and psychosocial health and wellbeing**. There are e**vidence gaps on the use of emerging technology in the workplace and its impact on OSH**. The rapid reviews of six key technology areas outline these dynamics and highlight areas where future research is needed. A wide range of technologies are used by practitioners to protect workers' safety and health

Safetytech, defined as "the collective term for technology, products and services that are starting to significantly enhance safety management in safety-critical industries and infrastructure",("The Safetytech Market | Lloyd's Register Foundation" 2020) refers to **the use of emerging technologies to address health and safety challenges** (Safetytech Accelerator 2023). Various technologies have been used by practitioners to promote workers' health, safety and wellbeing and reduce their exposure to risks (see examples in Box 2). Rather than using specific technologies in isolation, safetytech is often comprised of a combination of technologies working together (Lloyd's Register Foundation 2020). Technologies focused on connectivity such as the Internet of Things (IoT) and 5G (or fifth generation wireless technology)("What Is 5G Technology? | McKinsey," n.d.) are important in enabling this 'layering' of safetytech. In addition to capturing OSH data (for instance, through drones or wearables), safetytech (particularly AI-based technologies) can be used to analyse and interpret data to prevent risks and enable more effective solutions (Lloyd's Register Foundation 2020).

Box 1. Safetytech examples

- Use of **AI technology** to automate health and safety risk assessments (Safetytech Accelerator 2023) and to gather and analyse OSH data (Safetytech Accelerator 2023; Lloyd's Register Foundation 2020), including making predictions about the future (National Safety Council 2024). **Computer vision** is a form of AI technology that can simulate accidents and detect near-misses to prevent workplace accidents and support better training.
- Using **collaborative robots (cobots)** (Safetytech Accelerator 2023) or **drones** (Lloyd's Register Foundation 2020) instead of people to undertake dangerous tasks in the workplace (Safetytech Accelerator 2023)
- Deployment of **wearable devices** that monitor workers and/or working environments (see 3.2.3) – a fast-growing area of safetytech (Lloyd's Register Foundation 2020)
- Use of **Augmented Reality (AR)** and **Virtual Reality (VR)** for safety training and instruction (Lloyd's Register Foundation 2020; National Safety Council 2024) and risk assessment (see 3.2.5)
- Using **digital twins** to monitor OSH risks in real-world working spaces (Safetytech Accelerator 2023)
- Implementing **IoT technology** to capture real-time OSH data and enable quick responses to hazards (Lloyd's Register Foundation 2020)
- Integrating **technology that tracks employees' locations** and/or warns them when they enter hazardous or restricted areas (National Safety Council 2024)
- Deploying **smart sensors** to monitor employees' position in relation to potential hazards and to detect and prevent collisions (National Safety Council 2024)
- Making available **chat bots** providing OSH information and advice
- Deploying **exoskeletons** which can help eliminate OSH risks to humans in high-risk settings

1. Psychosocial risks refer to aspects of work organisation such as long working hours, high work pressure, lack of work-life balance, lack of job autonomy, difficult social interactions and exposure to harassment, violence and bullying in the workplace that are associated with negative health and wellbeing outcomes, particularly work-related stress (Eurofound and EU-OSHA 2014).

Alongside the purpose(s) for which it is introduced, s**afetytech may have unintentional or unexpected consequences**. One interviewee commented that even technologies introduced with the aim of protecting workers' safety and health may have unforeseen negative consequences. For example, drones in manufacturing could reduce workers' exposure to physical hazards but at the same time make them more sedentary, which carries its own risks for physical wellbeing. Another example would be workers paying less attention when replying on safetytech, increasing the risk of incidents associated with human error (Safetytech Accelerator 2023).

2.1.1. Technologies introduced for other purposes such as improved productivity and efficiency may have profound implications for workers' safety and health

As evidenced through expert stakeholder interviews, emerging technology impacts OSH beyond applications specifically aimed at workers' safety and health. Organisations may introduce new technologies for a wide variety of purposes including improved productivity and efficiency. Two interviewees felt that for many businesses, financial motivations were more pressing than safety considerations. One interviewee considered that the distinction between safetytech and other OSH-relevant technologies is not always clear-cut since certain technologies (for instance, AI-based technologies or collaborative robots [cobots]) may be introduced for OSH as well as other purposes. Regardless of the purpose for which they were introduced, emerging technologies may affect workers' health and safety (see examples in Box 2).

Box 2. Technologies beyond safetytech that interviewees consider had OSH implications

- The use of **AI** – in particular **Generative AI** – which could pose risks to workers in terms of privacy and security, or psychosocial risks alongside OSH benefits.
- The use of **Algorithmic Management** to manage employees, where risks for workers are primarily psychosocial (see 3.2.1)
- **Cobots** which can be implemented to improve efficiency and productivity in industrial settings which can pose physical and psychosocial risks to humans (see 2.2.6)
- **Quantum computing** enables vast amount of data to be harvested, which could be leveraged to protect workers from OSH risks, but may also introduce new risks
- Technologies that enable connectivity including **IoT, 5G and blockchain**.

Although there are exceptions – for instance, wearable devices to monitor workers' stress levels (Pasquale et al. 2022) – safetytech is often focused on preventing and managing physical rather than psychosocial risks. **However, safety tech and other technologies used in the workplace may have profound implications for workers' exposure to psychosocial risks** (European Agency for Safety and Health at Work 2018). For example, the use of new technologies in the workplace may affect working hours and work pressure, as well as social relationships at work. New technologies may contribute to work-related stress, particularly those used to assess workers' job performance (see section 2.2.1). For office/desk-based workers, exposure to psychosocial risks may be the prime or sole impact of new technologies.

Emerging technologies may contribute to high work pressure and/or poor work-life balance if workers must process a large amount of data ('techno overload') or if their use blurs boundaries between work and private life (European Agency for Safety and Health at Work 2018). Certain technologies may lower job autonomy, if some decisions (e.g., setting the pace of work) are partially taken over by machines. Worker monitoring – including Algorithmic Management (see 3.2.1) – may contribute to stress and burnout (European Agency for Safety and Health at Work 2018). In addition to the impact on day-to-day working conditions, the potential for technology to render a workers' job obsolete – whether real or imagined - may be a source of stress. Moreover, if technologies replace interpersonal interactions, they may weaken and undermine social relationships at work.

When it comes to broader technologies – particularly those such as Algorithmic Management used for surveillance purposes (see 3.2.1) -- the literature often focuses on their potential to expose workers to new and different OSH risks. However, **emerging technologies can help workers to feel better protected from health and safety risks**. A survey of nearly 5,000 UK employees found that the perceived impact of AI on different aspects of job quality (some of which align with psychosocial risks) was predominantly positive (Soffia, Leiva-Granados, et al. 2024). On average, UK employees felt that AI had allowed then more flexibility and decision-making power at work, had improved their career prospects and enabled better communication in the workplace (Soffia, Leiva-Granados, et al. 2024). The only facet of job quality perceived to be negatively influenced by AI was job insecurity (Soffia, Leiva-Granados, et al. 2024), reflecting concerns about jobs being 'taken' by machines.

2.1.2. Various challenges are associated with developing a robust evidence base on the OSH implications of emerging technology

Employer surveys have collected data on awareness and use of emerging technologies (National Safety Council 2024), including safetytech (National Safety Council 2024) and wider technologies such as AI (European Commission 2023; Hayton et al. 2023). Other surveys conducted with employees capture data on how often they are exposed to emerging technologies in the workplace (Soffia, Skordis, et al. 2024). Overall, however, **employers' appetite for and use of emerging technologies is not well understood**. This is partly because this is such a rapidly changing area: '*the minute you finish one [workplace] survey, the technology has already evolved*'. Employers can be reticent to share information about which technologies they are using and how, not wanting to lose any competitive advantage by making this information public. The 'how' is important here since technologies are often versatile and can be used in a different ways.

There is often **a lack of evidence regarding the impact of emerging technologies on OSH**. Benefits associated with new technologies can be difficult to quantify since OSH data collection is focused primarily on risks and incidents. The absence of risks or incidents is not directly observed, at least not without a robust counterfactual (which is rarely the case), making it difficult to substantiate a positive impact:

> *'It's sometimes difficult to quantify and measure good health and safety performance, good health and safety is the absence of things going wrong and that sometimes are quite intangible, aren't they? Whereas you know risk, you can potentially count and quantify incidents, accidents, even, you know, put some monetary measures on the impact of those… It's really hard to quantify what hasn't happened.'*

There can be challenges associated with gathering evidence on the long-term impact of new technologies, for instance on chronic conditions, since these take time to develop and may be more difficult to attribute to specific technological changes. Understanding the impact of technologies is also hampered by a lack of information sharing, with employers likely holding more OSH data than they share with regulators or other stakeholders. Moreover, employers may not collect data on the OSH-related impacts associated with new technologies. There could be a variety of reasons for this (e.g., lack of awareness or knowledge), but one factor could be that employers lack motivation to analyse and take steps to address OSH risks unless there is a business incentive to do so.

Research studies have been conducted looking at the OSH impact of specific technologies (see section 2.2), but this evidence base is incomplete and uneven. Examples of the deployment of specific technologies have been published as case studies (Safetytech Accelerator 2023), but naturally these examples focus on more successful applications of and on benefits more than risks. Some research may be funded and publicised by those with a financial interest in promoting the use of specific technologies, leading to lower trust from experts.

Taking all things into consideration - and reflecting on the limited evidence base on which to base decisions - organisations may deploy technologies without a good understanding of the implications these have for workers.

2.2. Topic reviews of six key technologies

This section presents findings from a scoping of the evidence on six emerging technologies with implications for OSH.

As outlined in the methodology section (Section 2), the shortlisting of key technologies was based on a preliminary assessment of their relevance and impact to the OSH field, as well as the volume, nature and quality of safety-related evidence. Feedback was gathered from experts who participated in the workshop about size of the **potential impact of specific technologies on OSH**.

Table 2. Summary of findings from the scoping review: key technologies and OSH

Area		Volume of evidence	Nature of evidence	Quality of evidence[1]
	Algorithmic Management	Moderate	Primarily qualitative, some review studies Focus is gig economy	Low
	Emotional AI	Low	Little empirical research	Low
	Wearable devices	Low	Some worker surveys Focus on acceptability	Low
	Safety-focused smartphone applications	Moderate	RCTs and pilot evaluations Systematic reviews	Moderate-high
	Augmented and Virtual Reality	Moderate	Some RCTs and systematic reviews	Moderate
	Collaborative robots (cobots)	Low	Little empirical research	Low

1. The methodological rigour of sources was assessed using the Maryland Scientific Methods Scale, as well as a qualitative summary of the limitations of each source.

A key theme that emerged from the workshop was how complex this impact can be to assess. In terms of their impact on OSH, some technologies may be more '*transformative*' than others, having a larger and more profound impact on workers and the workplace. Experts commented that the more transformative technologies from an OSH perspective were those that eliminated or drastically reduced exposure to hazards and/or technologies that resulted in new or different ways of working. Technologies that seek to 'nudge' workers or promote behaviour change, although they may have important uses, were seen as less transformative. Other considerations may also factor into an assessment of (potential) impact. Certain forms of emerging technology may be highly influential for those who use or are exposed to them, yet largely irrelevant to many workers if use is restricted to a small number of workplaces in specific industries. Another consideration is *for whom* technologies have an impact, since technology used in an occupational context may affect the safety of customers/clients etc. as well as workers. Experts consulted as part of the scoping review emphasised the importance of applying a broad safety lens to this issue rather than focusing exclusively on workers and the workplace.

Table 2 provides a high-level overview of indicative findings relating to the volume, nature and quality of evidence on the OSH implications of six technologies selected for more in-depth scoping. It is important to note that whilst these have been treated as separate topics for the purposes of the scoping review, there are likely to be technologies or applications that integrate and combine these elements, for instance Algorithmic Management incorporating Emotional AI or data from wearable devices inputting into Algorithmic Management.

2.2.1. Algorithmic Management

Algorithmic Management systems are those which use software to track, evaluate and manage workers, carrying out functions that may have previously been carried out by human managers (International Labour Organization 2024). These systems are clearly focussed on workplaces, but are not necessarily introduced to improve worker safety and health. By contrast, Algorithmic Management is namely introduced to improve efficiency in workplaces, or even enable entire labour markets (such as digital labour economy occupations, such rideshare driving roles) (Lee et al. 2015).

Despite widespread concern about the OSH impact of Algorithmic Management, the evidence base is limited

Algorithmic Management is not generally introduced for OSH purposes but may nonetheless have important consequences for workers' exposure to risks. Algorithmic Management was identified by workshop participants as one of the more '*transformative*' technologies in relation to OSH. A growing body of evidence indicates that Algorithmic Management has wide ranging consequences for OSH, most notably increased exposure to psychosocial risks and work-related stress. However, despite widespread attention and deep concern about this issue, empirical research on the topic remains relatively scarce and dominated by small-scale qualitative studies. The majority of empirical studies focus on the gig economy, meaning that the impact of Algorithmic Management on workers in more traditional employment situations is less well understood (Kinowska and Sienkiewicz 2023).

Algorithmic management may increase workers' exposure to psychosocial risks

A systematic review of Algorithmic Management in the gig economy highlights[1] **high and/or unpredictable workload** as a key risk (Bérastégui 2021). This is supported by qualitative research with gig economy workers in the US (rideshare drivers), who reported feeling pressured to accept a high volume of rides (Zhang et al. 2022). A **lack of job autonomy and control** is another psychosocial risk associated with Algorithmic Management in the gig economy (Bérastégui 2021). However, in some cases Algorithmic Management is paired with a high degree of autonomy for workers, for instance in selecting their working hours, and this is valued by some gig workers (Felix, Dourado, and Nossa 2023). Another factor that may contribute to **work-related stress** is a lack of transparency in how algorithms evaluate and often rank gig workers' performance (the 'information vacuum') (Reid-Musson, MacEachen, and Bartel 2020; Möhlmannn, Salge, and Marabelli 2023), although workers may test out hypotheses regarding how the algorithms work (Möhlmannn, Salge, and Marabelli 2023) and/or try to 'game' the system (Bucher, Schou, and Waldkirch 2021). A survey conducted across a range of European countries found that a clear majority of workers believe that the lack of transparency regarding Algorithmic Management is unfair (Holubová, n.d.). Algorithmic Management in the gig economy has been associated with **weak interpersonal relationships** (Vignola et al. 2023) and **lower levels of organisational trust**: '*an awareness of the imbalance in power between themselves and the platforms causes many workers to feel that they are being cheated and exploited, leading them to harbor resentment towards the platforms and the algorithms that manage them. Specifically, workers often trust a human in a management position to execute decisions that would be beneficial to both the company and its employees, while they are more cautious of errors and biases integrated into algorithms*' (Vignola et al. 2023, 8). The finding that humans are trusted more than algorithms when it comes to people management is also supported by other research (Lee 2018).

Workers in more typical employment relationships may be better placed to push back on and contain risks associated with Algorithmic Management

The use of Algorithmic Management is also widespread outside of the gig economy and affects a large number of workers in more traditional employment (Holubová, n.d.), who may be subject to similar risks. A survey of UK employees found far more people felt the amount of surveillance at their workplace had worsened than improved over the past three years due to new technology (Soffia, Leiva-Granados, et al. 2024). Analysis of a large-scale workplace survey conducted in the EU (plus the UK) shows that across all

1. The gig economy refers to 'a market system in which companies or individual requesters hire workers to perform short assignments. These transactions are mediated through online labour platforms, either outsourcing work to a geographically dispersed crowd or allocating work to individuals in a specific area' (Bérastégui 2021, 5).

sectors and industries, algorithmic management [1] is associated with **lower levels of wellbeing** for workers (Kinowska and Sienkiewicz 2023). The impact of algorithmic management on workers' wellbeing operates partly through **low job autonomy**, since this is positively associated with wellbeing (Kinowska and Sienkiewicz 2023). Compared to those in the gig economy, workers in more conventional working arrangements may be better placed to negotiate on aspects associated with negative outcomes for workers. A case study of a call centre in Germany found that the Works Council successfully negotiated a compromise with management whereby Algorithmic Management would not be used to monitor the performance of individual workers, with data only analysed at an aggregate level (Doellgast, Wagner, and O'Brady 2023). Not all workers will have the ability to resist and challenge working practices perceived to be detrimental to their health and wellbeing. However, even within the gig economy, researchers have documented efforts to resist and subvert Algorithmic Management (Reid-Musson, MacEachen, and Bartel 2020).

Risks associated with algorithmic management may be mitigated by the design of specific tools and technologies. Participatory research with workers in the gig economy (rideshare drivers) identified design solutions to mitigate risks including greater emphasis placed on consistency and tenure in worker ratings and platforms (rather than rewarding new drivers), facilitating peer-to-peer information sharing and introducing 'nudges' to promote workers' wellbeing (Zhang et al. 2022).

2.2.2. Emotional Artificial Intelligence

Emotional AI is "*the ability of machines and devices to extract data of a person's emotional state by reading their facial expressions, body language, skin conductance level, eye movement, voice tone, respiration, and heart rate variability, as well as machine learning of images and words*" (Mantello et al. 2023, 97). Examples of the use of EAI in OSH contexts include:

- Identifying the mood of employees to assess their wellbeing (e.g,, using camera or audio to assess facial expressions or speech signals)[2].
- Monitoring employees' level of engagement and attentiveness, including in meetings[3].
- Detecting the tone of customer service interactions[4].
- Using an AI chatbot to identify patterns associated with workplace harassment[5].

1. Measure informed by four items: Does this establishment use data analytics to monitor employee performance? Does this establishment use data analytics to improve the processes of production or service delivery? Robots carry complex series of actions automatically, which may include the interaction with people. Does this establishment use robots? For how many employees is the pace of work determined by machines or computers?

2. The Japanese company Empath, cited in Mantello et al (2023b).

3. Described in Mantello et al. (2003a).

4. The US company Cogito, cited in Mantello et al. (2023b).

5. US company Spot, cited in Mantello et al. (2023b).

Emotional AI may have an impact on worker's bio-psycho-social health

One of the main OSH risks associated with Emotional AI in the literature is that it may increase workers' levels of **stress and anxiety**, particularly if it forms part of performance management (Roemmich, Schaub, and Andalibi 2023). Elevated work stress may have implications for workers' **physical wellbeing**, for instance resulting in raised blood pressure or depleted energy levels (Roemmich, Schaub, and Andalibi 2023). Roemmich et al. (2023) found that workers subject to Emotional AI described having to engage in additional '**emotional labour**', which could be a drain on their energy. One interviewee in this study who had been subject to Emotional AI described making efforts to convey false positivity after having been reminded to 'smile more'. Another interviewee described how due to Emotional AI surveillance, they felt pressure to maintain a positive demeanour in customer service interactions even when subject to racist and sexist abuse. Part of the emotional labour associated with Emotional AI may be workers suppressing their 'true' emotions, thereby preserving their privacy.

There is some indication that workers may adapt their behaviours due to Emotional AI

The possibility of employees changing their behaviour to adapt to Emotional AI is also highlighted in a survey conducted by Corvite et al. (Corvite et al. 2023). One survey participant remarked: "*You could not be yourself and roll your eyes at your Supervisor or co-worker if you felt the urge, you would have a constant feeling that big brother is watching and you are not alone.*" (Corvite et al. 2023, 20). From this perspective, Emotional AI may result in a **loss of autonomy** for workers, who are no longer free to express themselves fully and must 'self-police' their emotional expressions.

Emotional AI may erode trust and relationships at work

Another concern raised in the literature is that Emotional AI may erode trust and weaken social relationships at work. Workers interviewed by Roemmich et al. (2023) expressed concerns about how Emotional AI may contribute to tension between employers and employees. Interviewees in this study, including workers subject to Emotional AI technologies at work, saw the use of emotional AI as indicative of a lack of trust from their employer. Some interviewees described choosing to discuss their concerns about Emotional AI with colleagues in person so that their conversation was not recorded, which could feed into digital surveillance from their employer. Conducting a survey of 1,015 university students ('future job seekers') in Japan, Mantello et al. (Mantello et al. 2023) found that those with a lower household income were more concerned about the use of Emotional AI in workplace management. The authors posit that students with a higher income are likely to end up in higher-status occupations, meaning that they are more likely to be the managers who use Emotional AI to recruit and monitor their employees rather than workers who are subject to these technologies. The authors infer that "*left unregulated, EAI will only **exacerbate labor relation tensions**, especially conflicts that may arise due to culture, gender, social class, ethnicity and*

attitudinal disposition" (Mantello et al. 2023). Another survey of 395 US adults found that 20% of participants expressed a concern about Emotional AI creating or intensifying power imbalances in the workplace (Corvite et al. 2023), indicating that this concern is shared more widely.

Emotional AI may help identify workers' health needs, yet scepticism remains regarding its ability to safeguard health and safety. Contrary to these concerns, Emotional AI may be used specifically with the aim of improving workers' health, safety and wellbeing. In the context of the rise in remote/hybrid working since the COVID-19 pandemic, Emotional AI may be used by employers to i**dentify health and wellbeing issues**, including mental health conditions. Emotional AI may also have value in protecting workers from harms posed by others, for instance by **identifying workplace harassment** (Mantello et al. 2023).

However, scepticism is expressed in the literature from both researchers (Mantello and Ho 2024) and research participants (Corvite et al. 2023) about the potential for Emotional AI to protect workers' health and safety. A survey of US adults found that around a third of participants (32%) did not perceive there to be any benefits associated with Emotional AI in the workplace (Corvite et al. 2023). Only a minority of participants expected Emotional AI in the workplace to have benefits for employees, in terms of recognising support needs (31%), health conditions (16%) and burnout/over-work (15%) and identifying workers who may post harm to themselves or others (11%) (Corvite et al. 2023).

Workers are sceptical that EAI will reduce bias and discrimination

Another risk discussed in the literature is the potential for EAI to lead to bias and discrimination in the workplace. Theoretically, Emotional AI technology could reduce bias and discrimination by enabling employers to make decisions based on objective data rather than subjective assessments. However, a survey of US adults found that only a small minority (3%) expected Emotional AI to have this benefit (Corvite et al. 2023). In practice, Emotional AI may not be accurate and AI-based tools may have implicit biases, contributing to labour market and workplace inequalities. Interviews with workers conducted by Roemmich et al. (2023) indicate that the potential for inaccuracy is a concern for those subject to Emotional AI technologies (or those who may be subject to them). One interviewee commented on how she did not have the 'friendliest face', expressing concern that this may negatively impact her job performance in the context of EAI. Another interviewee described being 'forced' to reveal her pregnancy to her employer after they expressed concerns about her emotional state based on EAI surveillance, changes she attributed to her pregnancy. Concerns about bias and discrimination associated with EAI in the workplace are also highlighted by a survey conducted by Corvite et al. (2023). One survey participant commented: "*there is already a bias in the workplace for minorities and women, these systems could be used as 'evidence' in any unjustness, or oppression, by blaming it on mental instability.*" (Corvite et al., 2023: 18).

Despite the interest generated by EAI in the workplace, there is a dearth of evidence foregrounding workers' views and experiences (Roemmich, Schaub, and Andalibi 2023). One of the few identified sources to conduct an empirical exploration of workers' experiences of Emotional AI is Roemmich et al. (2023), who conducted semi-structured interviews with workers in the USA (n=15), some of whom (n=6) have been subject to Emotional AI technologies[1]. Research participants were varied in terms of age, gender and ethnicity, as well as industry sector. However, as a small sample, the findings are not generalisable to the wider workforce. Some studies explore attitudes towards Emotional AI and perceived risks and benefits, usually based on survey data (Mantello et al. 2023; Corvite et al. 2023). However, perceived risks and benefits associated with Emotional AI in the workplace may not be fully aligned with real-world impacts, not least because many research participants will not have been (knowingly) subject to these technologies.

2.2.3. Wearable devices

Wearable devices are technologies used to monitor individuals' physiological and psychological state. These can include smart watches, Bluetooth-enabled heart rate monitors, insole devices, exoskeletons and smartphones ((Dodoo et al. 2024).Wearable devices are not solely used for OSH purposes – they are used in the health sector, for example, and are commonly used by individuals for fitness and health tracking (Kang and Exworthy 2022; Wall, Hetherington, and Godfrey 2023).

Wearable devices have a wide range of OSH applications

Increasingly, wearable devices are used in the workplace to protect workers from health and safety risks, particularly in certain sectors such as construction (Dodoo et al. 2024; Häikiö et al. 2020). Wearable devices are used for **real-time monitoring of health and safety hazards in the working environment**. This can include tracking workers and informing them of hazardous areas to avoid (Pasquale et al. 2022) and detecting when workers are wearing improper safety equipment or performing dangerous tasks (Flor-Unda et al. 2023). As well as identifying risks in the working environment, wearable devices are used to **monitor workers' physical and/or psychological wellbeing**. One review article looking at the use of wearable devices in the construction industry lists various types of data collected including physical metrics (falls, back pain, fatigue, heat or cold, dehydration) and psychological metrics (stress, fatigue, happiness/wellbeing) (Abuwarda et al. 2022). One review article found that stress was the most common condition measured by wearable devices, followed by fatigue, wellbeing and attention (Pasquale et al. 2022). In measuring physical and psychological factors, wearable devices may help organisations to identify and manage risks (Khakurel, Pöysä, and Porras 2017), although none of the identified sources consulted employers about how they use and respond to data produced by wearable devices.

1. The authors describe this as 'cognisant experience', recognising that workers may be subject to EAI technologies without their knowledge or awareness.

Evidence on how wearable devices influence OSH outcomes is limited

Several studies examine the use of wearable devices in OSH, including in specific sectors such as construction (Abuwarda et al. 2022; Chen et al. 2024; Häikiö et al. 2020) and healthcare (Abuwarda et al. 2022). Most of the identified sources (including systematic or literature reviews) describe various OSH applications for wearable devices. Some studies collect primary data on the acceptability of wearable devices in the workplace (Häikiö et al. 2020; Ibrahim, Simpeh, and Adebowale 2023; Nnaji et al. 2021; Schall, Sesek, and Cavuoto 2018; Tindale et al. 2022). Hower, there appears to be l**ittle empirical evidence to substantiate the impact of these devices on OSH.**

There are concerns that wearable devices may transfer the burden of OSH responsibility onto employees

As well as their intended OSH-related benefits, wearable devices may have wider impacts, including unanticipated consequences. A key risk discussed in the literature is the potential for wearable devices to infringe on privacy of users by capturing information which may be considered personal or private (an issue also noted in relation to other technologies such as algorithmic management and emotional AI) (Abuwarda et al. 2022; Pasquale et al. 2022; Chen et al. 2024; Häikiö et al. 2020; Khakurel, Pöysä, and Porras 2017; Nnaji et al. 2021; Tindale et al. 2022), which could create individual as well as union disagreements with management upon the implementation of these technologies. Another risk mentioned is that too much trust could be placed in devices, leading safety risks not captured by these devices to be neglected (Flor-Unda et al. 2023).

Wearable devices may also **push the burden of OSH management onto the employee** rather than the employer, adding to work pressure and work-related stress. For this and other reasons there may be resistance from workers (Flor-Unda et al. 2023; Nnaji et al. 2021), which could undermine compliance. However, survey data from studies conducted in the United States and Finland indicate widespread willingness to adopt wearable devices designed to protect against OSH risks (Nnaji et al. 2021; Häikiö et al. 2020; Schall, Sesek, and Cavuoto 2018).

2.2.4. Smartphone applications for OSH

OSH-related smartphone applications are mobile apps that can be used by workers to prevent and manage physical and mental health conditions in the workplace. These fall into the broad category of general smartphone applications, which can be used for any number of purposes, and into the slightly narrower category of smartphone apps for health, which can be used by ordinary consumers outside of the OSH context, as well as by workers. In this instance, we understand OSH-related smartphone applications as those with specific aims to address challenges that workers may face in occupational contexts.

Rigorous evidence is available about the impact of OSH-related smartphone applications

A growing body of literature presents evidence on the effectiveness of safety-focused smartphone applications in occupational contexts, including high-risk industries such as construction (Anger et al. 2018; Hossain et al. 2023; Pérez Carrasco et al. 2024), healthcare (Sanatkar et al. 2022; Taylor et al. 2022), agriculture (Chavez Santos et al. 2022), transport (Davidson et al. 2020; Wilson et al. 2023) and policing (Vera-Jiménez et al. 2019). The scoping review identified **several RCTs** evaluating the impact of specific applications (Alshagrawi and Abidi 2023; Bartlett et al. 2022; Bort-Roig et al. 2020; Chavez Santos et al. 2022; M. Deady et al. 2022; Mark Deady et al. 2024; Monfries, Sandhu, and Millar 2023; Taylor et al. 2022; Weber, Lorenz, and Hemmings 2019; Wilson et al. 2023), as well as **systematic reviews** (Buckingham et al. 2019; Jung and Cho 2022; Paganin and Simbula 2020; Sevic et al. 2023) and a meta-analysis (Jung and Cho 2022), making this a **technology area with a relatively robust and well-developed evidence base**.

Evidence supports the use of smartphone applications in stimulating behaviour change

Several studies provide evidence to support the use of smartphone applications to **encourage workers to adopt healthy lifestyles** including physical activity levels (Alshagrawi and Abidi 2023; Bort-Roig et al. 2020; Jung and Cho 2022; Buckingham et al. 2019), alcohol consumption (Collins et al. 2020) and healthy eating habits (Wilson et al. 2023; Anger et al. 2018). An RCT found that a smartphone application monitoring sitting, standing and steeping (Walk@WorkApp) used by desk-based employees over a 13-week period reduced sedentary behaviour outside of working hours (Bort-Roig et al. 2020). However, no changes were observed during working hours (Bort-Roig et al. 2020), indicating that desk-based employees may have limited agency to increase their physical activity levels at work. Another RCT found that a health-based smartphone application used by airline pilots over a 16-week period was associated with various improved objective and subjective health indicators including sleep and intake of fruit and vegetables (Wilson et al. 2023). A third RCT found that a mobile-health intervention for workers was associated with increased physical activity levels and lower Body Mass Index (BMI) over a 3-month period (Alshagrawi and Abidi 2023). Systematic reviews (Buckingham et al. 2019; Jung and Cho 2022) and a meta-analysis (Jung and Cho 2022) conclude that there is reasonable evidence to support the use of mobile-health (mHealth) technology (which might include wearable devices as well as smartphone applications) to increase workers' physical activity levels.

Some smartphone applications seek to **promote safety-focused behaviour on the part of managers and supervisors**. An RCT found that the HEAT application targeted at the agriculture industry, which informs supervisors about hot conditions and provides recommendations to keep workers safe, was associated with lower levels of heat strain for employees when used over a 5-month summer period (Chavez Santos et al. 2022). The Total Worker Health Intervention, comprised of training for supervisors in the construction industry combined with a smartphone application used over a 14-

week period, was associated with an increase in supervisor support regarding healthy lifestyles (Anger et al. 2018). The study identified several positive changes for workers including improved sleep, lower blood pressure and reduced consumption of sugary foods and drinks (Anger et al. 2018). However, conclusions must remain tentative since the study lacked a robust counterfactual.

A range of physical and mental health benefits have been linked to OSH-related smartphone applications

A key area of focus in the literature has been the potential for smartphone applications to **improve workers' mental health and wellbeing**. High-quality evidence from RCTs supports the use of smartphone applications to improve workers' wellbeing (Taylor et al. 2022), lower their stress levels (Weber, Lorenz, and Hemmings 2019) and reduce symptoms associated with burnout (Monfries, Sandhu, and Millar 2023) and depression (Taylor et al. 2022; M. Deady et al. 2022). However, some studies find mixed evidence in terms of the impact of smartphone applications on outcomes relating to mental health and wellbeing. A three-arm RCT found that when combined with classes, a mindfulness app was associated with lower levels of psychological distress and high levels of mindfulness for workers (Bartlett et al. 2022). However, either alone or compared with classes, the app was not associated with lower stress (the primary outcome) compared to the control group (Bartlett et al. 2022). Some studies identify positive effects for health-related outcomes for workers but do not identify concomitant changes in worker behaviour or performance. A pilot evaluation (pre/post comparison) of *Anchored*, an app offering mindfulness and CBT to address depression in the working population, identified reductions in depressive symptoms and anxiety, improved wellbeing, lower stress, greater self-perceived resilience and reduced alcohol use at 5-week follow-up compared to baseline (Collins et al. 2020). However, no significant effects were observed in relation to work performance or absenteeism (Collins et al. 2020). An RCT found that a mindfulness application used by healthcare workers over a 4.5 month-period was associated with lower levels of stress and depression and improved wellbeing; however, the app was not associated with a reduction in sickness absence (Taylor et al. 2022).

2.2.5. Augmented and Virtual Reality

Augmented reality (AR) and virtual reality (VR) technologies are artificial environments generated using computer algorithms, creating a simulated and interactive world (Grassini and Laumann 2020). They are both mixed reality technologies – VR creates a completely virtual environment for users and AR incorporates virtual visuals into the user's real world (Li et al. 2018; Gao, Gonzalez, and Yiu 2019). In the OSH context, AR/VR are typically understood as one of many types of health and safety training technologies (also referred to as computer-aided technologies) which are used to deliver knowledge to users on hazard identification, avoidance response and reporting (Gao, Gonzalez, and Yiu 2019; Moore and Gheisari 2019).

A growing body of evidence supports the use of AR/VR in OSH training

A growing body of evidence supports **the effectiveness of AR and VR for the OSH training** when compared to more traditional training methods. This body of work includes randomised trials (Nykänen et al. 2020; Adami et al. 2021) and systematic reviews (Gong, Lu, Lovreglio, Lv, et al. 2024; Riches et al. 2024; Junaini et al. 2022; Gao, Gonzalez, and Yiu 2019). Existing evidence is heavily weighted towards the use of AR/VR in certain sectors, with most studies focusing on the construction industry (Li et al. 2018; Ahmed 2018; Moore and Gheisari 2019; Nykänen et al. 2020; Joshi et al. 2021; Bhoir and Esmaeili 2015; Gao, Gonzalez, and Yiu 2019; Adami et al. 2021; Gong, Lu, Lovreglio, Yang, et al. 2024).

A systematic review and meta-analysis exploring AR safety training solutions applied to thirteen industries (including high-risk industries such as construction, manufacturing, and transportation) concludes that there is evidence to support the effectiveness of AR in safety training (Gong, Lu, Lovreglio, Lv, et al. 2024). It details that **AR promotes enhanced engagement and active learning and participation** through its immersive and interactive nature, a finding also corroborated by others (Joshi et al. 2021; Gong, Lu, Lovreglio, Yang, et al. 2024). The meta-analyses conducted by Gong et al. (2024) found that compared to traditional training methods, AR has a positive impact on user experience but no measurable effect on **knowledge acquisition** (Gong, Lu, Lovreglio, Lv, et al. 2024). However, other studies identify positive effects for AR/VR on knowledge acquisition when compared to traditional training methods. An RCT found that compared to lecture-based training, VR training for construction workers was associated with improved knowledge, with the treatment group better able to identify hazards in the workplace (Nykänen et al. 2020). This study also suggests that workers may be better placed to apply this knowledge in the workplace following VR training, with the treatment group scoring higher on safety motivations and self-efficacy (perception that they could improve safety in the workplace) (Nykänen et al. 2020). A second randomised trial conducted with construction workers found that VR training was associated with improved safety knowledge and safety behaviour in operating robots compared to traditional in-person training (Adami et al. 2021).

Wider OSH applications such as using AR/VR to tackle work-related stress are less well explored

Other positive, although less commonly mentioned, benefits of AR/VR identified through the scoping review includes a **reduction in work-related stress and mental health benefits** (Riches et al. 2024). A systematic review found that VR promotes wellbeing in the workplace by improving relaxation and decreasing stress (Riches et al. 2024), making it a potential tool for stress prevention and management.

Several challenges associated with AR/VR identified in the literature

Authors do balance the strengths and opportunities associated with AR/VR technologies alongside their challenges. Namely:

- **AR/VR as resource intensive** (in terms of time and funding): AR/VR is associated with high development and implementation costs and time inputs (Adami et al. 2021; Moore and Gheisari 2019; Grassini and Laumann 2020).
- **Limited hands-on experience:** AR/VR lacks real-world, hands-on experience, which can limit learning and memory retention (Li et al. 2018).
- **Technical and practical difficulties:** Issues such as equipment overheating, difficulty operating technology and adverse physical side effects (Riches et al. 2024; Adami et al. 2021; Kim, Nussbaum, and Gabbard 2016).
- **Data privacy concerns:** Some participants express concerns about data privacy when using VR/AR (Riches et al. 2024).
- **Need for further evidence on AR//VR and OSH:** Although the evidence base is growing, studies call for additional evidence to support the use of AR/VR in OSH (Gao, Gonzalez, and Yiu 2019; Li et al. 2018), including data on adverse effects such as workplace injuries associated with AR/RV training (Gao, Gonzalez, and Yiu 2019).

2.2.6. Collaborative robots (cobots)

In the past, industrial robots were seen as replacements for humans which could complete dangerous or tedious tasks with accuracy and precision (Hentout et al. 2019). While robots would thus assist humans, they would typically operate in separate spaces from human workers. By contrast, cobots are '*robotic applications designed to work alongside humans in a shared workspace or in close proximity to humans*' (Eurofound 2024, pg. 5). To enable this coworking, cobots rely on sensors both to locate the position of human workers and to respond to their actions (Raffik et al. 2023).

Cobots have a wide range of potential applications

There **is limited empirical evidence for how cobots are used**, but certain studies provide examples– including the use of cobots for medication preparation and distribution in a hospital in Italy and for handling clinical samples in a Swedish hospital laboratory, supporting staff with these tasks amid high workforce pressures (Eurofound 2024). While these specific case studies are used to reflect managers' centring of both worker and patient safety in the decision to implement cobots, the evidence on why cobots are used in the broader landscape is nonetheless limited, and there is a wide gap in understanding the extent to which cobots improve OSH outcomes and how.

A lack of evidence limits our understanding of the OSH implications of cobots

Published review articles, while providing a helpful overview of potential safety implications for cobots and speculative views on their future impacts, also do not answer this question. Relevant reviews discuss the potential safety implications and considerations for cobots as well as other outcomes associated with them. Crucially, while these articles cover areas of interest to the intersection of cobots with OSH, they frequently engage in either technical discussions on the implementation and impacts of cobots or in hypotheticals and priority-setting for future research and policy. Review articles do not widely cover the real-world safety implications associated with cobots, reflecting a gap in existing scholarship. Scholars do recognise that this gap exists, and that scholarship on the technical impacts of cobots should be supplemented with an understanding of the real-world safety implications associated with cobots, or the so-called 'side effects' of technology (Keshvarparast et al. 2024; Neumann et al. 2021). This framing itself shows that OSH is not a core consideration in existing research on cobots.

Values such as the **sustainability and human-centricity of cobot use** (or the impacts of cobots on the environment, society, and the labour market, beyond mere productivity implications) are common concerns in the existing academic literature on cobots (Ghobakhloo et al. 2024; Grabowska, Saniuk, and Gajdzik 2022; Leng et al. 2022; Bonello, Refalo, and Francalanza 2024). Cobots' **effective integration into existing assembly lines and processes** is a key interest to other scholars, particularly for how this integration impacts human operators from a technical perspective (i.e. communication mechanisms and change in assembly line roles) (Bi et al. 2022; Panagou, Neumann, and Fruggiero 2024). The literature also includes articles on the **interoperability of cobots with other technologies such as digital twins(digital representations of industrial systems)**, highlighting their utility for better understanding the impacts of cobot use in industrial settings (Zafar, Langås, and Sanfilippo 2024; Safetytech Accelerator 2023).

There remains very little empirical evidence that centres the OSH impacts of cobots in the workplace. The empirical research that does exist on this topic centres on the setting of priorities for cobot safety and on understanding workers' perception of cobot safety. Nicole Berx at KU Leuven has published research on cobots including an empirical study on the validation of a tool to evaluate cobot safety readiness, in which industry participants rated and scored a cobot safety readiness matrix (Berx, Decré, and Pintelon 2024). Other authors have published relevant literature on the topic, including a study by Aaltonen and Salmi drawing on survey data from diverse individuals in cobot distribution, academia, and the manufacturing industry (Aaltonen and Salmi 2019). Other existing research on cobots frequently falls into the field of robotics, and covers issues such as ensuring that cobots are well-equipped to interact with humans, both through sensors and programming, and that humans can safely and effectively interact with them (Hentout et al. 2019; Petzoldt, Harms, and Freitag 2023). However, this does not integrate substantial OSH evidence, representing a limitation of existing research as it relates to cobots in OSH.

3. Conclusions

This scoping review highlights a limited, patchy and uneven evidence base relating to emerging technology and OSH. Cross-cutting challenges complicate and impede efforts to build and improve the evidence base, including the rapidly evolving nature of technology and commercial sensitivities and other factors that limit information sharing. Technologies are implemented for a variety of reasons, including to achieve efficiencies and cost-savings as well as for their safety and health benefits. However, OSH-related outcomes may not always be prioritised when assessing the impact of new technologies in the workplace. Whilst it is difficult to draw clear conclusions about the impact of the technologies discussed in this report on OSH, this uncertainty highlights the need for further research and investigation. In this concluding section, we reflect on the implications of the findings of this scoping review for the research agenda, pointing to priority areas where there is a need for future work from the Lloyd's Register Foundation and/or the wider research community.

There is a need for further research to better understand demand for and use of emerging technologies in the workplace. There is some survey data available on employer awareness, attitudes and use, but this is restricted to specific technologies. Moreover, whilst these large-scale estimates of the prevalence of employer adoption are important, this needs to be complemented by in-depth research to better understand how technologies are used in real-world contexts, by whom and for what purposes, recognising that this may vary across different geographical, industrial and occupational contexts, with technologies potentially used in ways that differ from their intended use. Improving our understanding of how technologies are used in an occupational context will provide a stronger foundation for understanding their impact on OSH.

Experts consulted as part of the scoping review emphasised that some technologies are more transformative than others, eliminating or drastically reducing exposure to OSH risks and/or radically changing ways of working. However, when we scoped the evidence on six key technologies (Algorithmic Management, Emotional AI, wearable devices, OSH-focused smartphone applications, cobots and AR/VR), we found that the evidence base is most well developed in relation to technologies that are arguably less transformational to existing ways of working, seeking to promote behaviour change (smartphone applications) or improve OSH awareness and knowledge (AV/VR for OSH training). There is a pressing need to strengthen the evidence base on the impact of more transformational technologies such as Algorithmic Management and Emotional AI, particularly in relation to their consequences for workers' exposure to psychosocial risks. Where empirical evidence does exist for these technologies, this is often comprised primarily of small-scale studies that lack a robust counterfactual. There is a need for investment in high-quality studies, including randomised trials, to provide robust estimates of how new technologies, some of which are already widely adopted, affect workers' safety and health.

A key theme that emerged from the scoping review is the importance of collecting data on the unintentional or unforeseen OSH-related consequences of new technologies. One aspect of this is recognising that some of the technologies with the greatest potential to influence workers' safety and health (e.g., Algorithmic Management, Emotional AI) are not safetytech (i.e. technologies introduced with the aim of protecting workers' safety and health). It is also important to document unplanned or unanticipated effects associated with safetytech, including the potential for technology adoption to contribute to complacency in addressing OSH risks in the workplace. From a research perspective, this means developing Theories of Change to better understand the theory behind interventions and designing impact studies to collect data on their unanticipated consequences as well intended outcomes.

Lastly, **there is a need to bring stakeholders together to share knowledge, data and best practice.** Efforts have been made to facilitate discussions between employers and OSH practitioners/regulators but experts consulted as part of this review felt that further collaboration would be highly beneficial. A central component of this work should involve collaboration with employers to address some of the barriers to sharing information and data, contributing to a better understanding of how and why emerging technologies are used in the workplace and what existing data (if any) is captured by employers on their OSH implications. There may also be scope to engage with organisations who develop safetytech and other relevant technologies to better understand the data and evidence they hold and to involve them in future efforts to strengthen the evidence base. Finally, is it crucial not to lose sight of the worker perspective and the importance of consulting workers during the design and development phase of technologies as well as their evaluation. Understanding these diverse views and the specific needs of different implementation contexts may help support the monitoring and use of emerging technologies for OSH purposes.

In summary, this report indicates that the establishment of the Global Safety Evidence Centre could add value by producing, collating and disseminating evidence about how emerging technologies are used in workplaces and particularly when it comes to more 'transformational' technologies, their impact on workers' occupational safety and health (including unforeseen consequences), as well as facilitating knowledge sharing and good practice in this area.

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Annex A: Interview guide

Table 3 below provides an overview of questions asked to stakeholder interviewees for this project.

Table 3: Interview questions

Number	Question
1.	Can you please tell me about your professional background and role at [organisation]? How does your role address OSH and/or emerging technology?
2.	Clearly, this topic is very broad. In your view, which emerging technologies are most important to consider from the perspective of occupational safety and health and why?
3.	Which emerging technologies have received a lot of attention from an occupational safety and health perspective? Which technologies have received less attention? Why do you think this is?
4.	What are the most high-risk industries when it comes to the impact of emerging technologies on occupational safety and health?
5.	For specific technologies mentioned: - What are the main OSH risks and benefits? - In what contexts? (industries/sectors/types of employees or workers) - What evidence exists on this topic? How would you describe the evidence base? Volume/nature/quality - What are the areas of uncertainty? What future research is needed? - To what extent is existing evidence being used by policy makers and practitioners?
6.	What are the opportunities and challenges associated with researching the impact of emerging technology on occupational safety and health?
7.	If you were going to conduct an evidence/literature review on a topic related to emerging technology and occupational safety and health, which topic would you choose and why?
8.	Is there anything else you'd like to add on this topic, including anything you wish you'd added to your earlier responses or anything you thought I might ask but didn't?