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Digital technologies in construction: A systematic mapping review of evidence for improved occupational health and safety

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ABSTRACT

There is accelerating development of digital Occupational Health and Safety (OHS) interventions in construction, but it is not clear whether they reduce the risk of injury and illness. This systematic mapping review summarized the state of the evidence and developed recommendations for practitioners and researchers. During a keyword search of scientific databases, 392 unique records were identified and 24 (~6%) were included in the review. The review was conducted within an Evidence Maturity framework developed for public health interventions, which outlines criteria for intervention. Studies are characterized by innovative application of a wide variety of technologies throughout pre-construction planning, construction execution, and worker training. Targeted hazards primarily included falls, struck-by incidents, and location-based hazards. Most studies focused on technology development and provided low to no evidence of improved work conditions or reduced injury/illness among construction workers. More evidence is needed before the digital solutions are promoted for widespread use. In order to achieve this, more attention need to be paid on the conflicting logics between the evidence maturity framework and the project logic in the construction practice.

1. Introduction

Construction remains a high-risk industry, and in many regions has the highest rates of serious injury and fatality. In 2020, more than a fifth of all fatal accidents at work in the EU took place within the construction sector [1]. In the US, the leading causes of workplace death among construction workers 16–64 years old at work in 2020 were falls from, out of, or through a building or structure, followed by other falls from one level to another, and finally struck by thrown, projected, or falling object [2]. Researchers and labour unions [3] alike have highlighted the need for effective health and safety interventions in construction. While large-scale, resource-intensive safety initiatives such as 'Stand down for safety' have demonstrated that interventions can be successful in the eyes of stakeholders [4], interviews with construction stakeholders show an appetite for solutions that not only improve safety, but which can also enhance productivity and quality [4].

Over the past decade, a variety of digital technologies have become available with the potential to bring health and safety benefits. For example, a recent review outlines how Building Information Modeling (BIM) which is primarily designed to enhance productivity and quality in building design and construction planning, can also be leveraged to increase occupational health and safety (OHS) [5]. During short pilots and simulations, the design and planning aspects of BIM have incorporated hazard tracking, rule-checking, and

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other safety functions, often by integrating other technologies like mobile sensors [5]. A review of computer vision applications in construction outlines opportunities for improving worksite safety with automated efficiency, but acknowledges that substantial challenges remain in method validation and evaluation [6]. Unmanned aerial vehicles (i.e. flying drones) have similarly been proposed as contributors to digital OHS efforts, but a recent summary of potential challenges suggests drones introduce a new set of hazards [7]. Although there is clearly a great need for OSH interventions in construction and great potential for digitalization to contribute, the full implications of long-term implementation of digital solutions has not yet been summarized. There remains an evidence gap regarding which digital OHS solutions are effective, and to what degree, under real working conditions.

Historically, the quality of OHS intervention studies in construction has not been high, with Goldenhar et al. noting that most OHS intervention studies had "small samples and non-experimental or quasi-experimental designs with uncontrolled sources of bias" [8]. New safety interventions should be evidence-based before recommending wide-spread adoption, what it means for this standard to be met might not be clear to construction stakeholders. Standards from the Society for Prevention Research outlines criteria for levels of intervention evidence maturity: efficacy, effectiveness, and dissemination (see Fig. 1) [9]. For the purposes of this article, this framework has been expanded to include a *development phase* to precede these steps, in acknowledgement of the R&D character of emerging digital technology. *Efficacy* refers specifically to the ability of an intervention to effect positive outcomes under ideal or semi-controlled conditions (i.e. what the intervention *could* do); whereas *effectiveness* refers to the ability of an intervention to produce positive outcomes under more real-world conditions when implemented under the constraints of a workplace context (i.e. what the intervention *actually* does). Even when simulations, lab tests, or short-term trials can demonstrate the efficacy of an intervention, the real-world effectiveness may be hampered by barriers stemming from contextual or organisational factors. For example, while lab studies show that exoskeletons can reduce physical loads during lifting [10], under real working conditions there are substantial barriers to effective implementation, including limiting some movements or work performance, overheating, and social pressure [11, 12]. Evidence for dissemination is one further step, when large-scale feasibility and logistics favour the promotion and adoption of the intervention to the wider community [9]. The evidence standards at each of these steps are cumulative, building on the research base of the prior step, and not all interventions meet the criteria to progress through this maturity process.

The emerging field of digital OHS technologies is rapidly-evolving, and the construction sector presents a unique set of constraints and incentives for successful adoption. Although there have been reviews of digital technologies in construction, many have examined mainly bibliometrics [13] or focused on the 'state of the art/technology' [14,15], rather than the 'state of the evidence' from a public health perspective. Thus, there remains a need to examine and summarize the state of the evidence for digital OHS interventions so that appropriate recommendations can be made to industry stakeholders. Applying the public health-inflected evidence maturity framework (Fig. 1) is a novel approach but a fitting one; construction safety has similar 'life and limb' implications as other major public health issues, along with the socio-economic repercussions of getting interventions right (or wrong). Conducting a review with an evidence maturity lens would serve to synthesize information on digital OHS interventions in construction into useful recommendations.

The goal of this systematic mapping review is to summarize the state of the evidence for digital health and safety technologies within the construction industry and to develop recommendations for practitioners and researchers. To maintain applicability to industry, the review draws on empirical studies undertaken in real-life construction settings. The specific research questions guiding the review were:

1. What is the evidence base for digital OHS technologies in the construction industry?
2. What are the remaining gaps in this evidence base, and what types of research can be recommended to address them?

2. Methods

This study adopted the systematic mapping review approach as described by Grant et al. [16] Consistent with their Search,

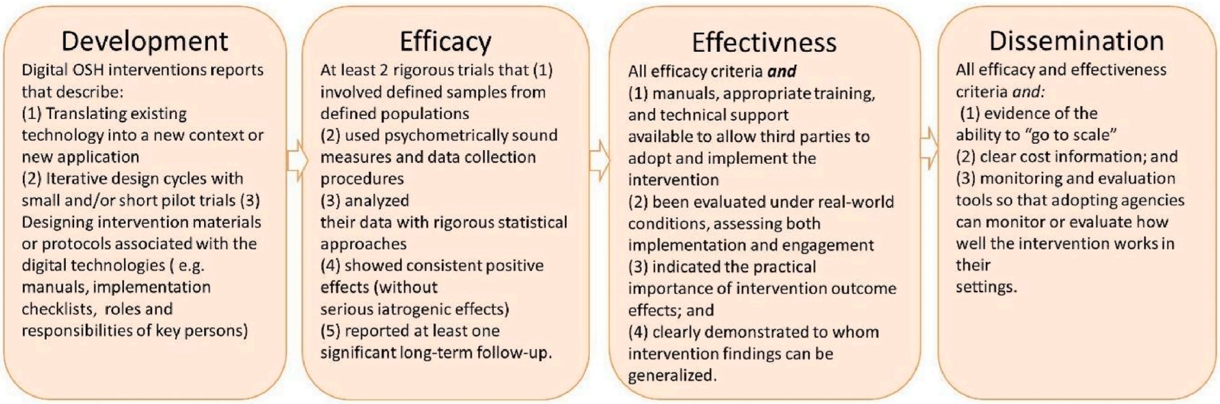

Fig. 1. Evidence Maturity framework for public health interventions with criteria for Efficacy, Effectiveness, and Dissemination adapted from Flay et al. [7] The preceding 'Development' step has been added for the present study.

Appraisal, Synthesis and Analysis (SALSA) framework [16], the aim of the analysis was to map out and categorize existing primary research literature evaluating digital interventions for occupational health and safety in construction industry, in order to identify gaps in research literature that could help direct recommendations for future research.

2.1. Search strategy

A search of electronic published databases was conducted on March 25, 2022 from: Scopus, Web of Science and PubMed. No date limits were set for a search combining four conceptual groups of synonyms for “construction”, “occupational health and safety”, “digital technology”, and “intervention”. Synonyms within concept groups were combined with “OR”, all conceptual groups were combined with “AND” (see Table 1 for a full list of search terms).

2.2. Inclusion and exclusion criteria

Eligible records were full-text, peer-reviewed, English-language primary research articles with available full-text that reported the evaluation of a digital OHS intervention on a real construction worksite. No exclusions were made based on study design, study quality, or date of publication. Identified records were screened for adherence to the inclusion criteria at the title, abstract, and full-text stages using the operationalized inclusion questions outlined in Table 2. Screening of any ambiguous records was resolved through discussion and consensus between the authors; inclusion and exclusion criteria were refined as needed based on this discussion.

2.3. Data extraction

The included studies differed considerably in their designs and characteristics, thus it was not considered appropriate to perform meta-analyses. Instead, data on the intervention and evaluation were extracted to serve a synthesis of the main findings by intervention type. Table 3 describes the specific categories of information extracted from each article.

2.4. Study quality assessment

Given that construction workplace safety is a matter of life and limb, the demands for a robust evidence base is as high as it is for studies of medical treatments and population health. Therefore, our quality ranking approach, outlined in Table 4, is inspired by those used in medical and clinical sciences. For example, the checklists developed and promoted by the Equator (Enhancing the QUAlity and Transparency Of health Research) STROBE initiative (Strengthening the reporting of observational studies in epidemiology) [17]. Note that study quality is a characteristic of each individual study, and is distinct from evidence maturity which looks at the sum total of studies on a topic.

3. Results

3.1. Search and screening results

The results of the search and screening project are summarized in a PRISMA diagram in Fig. 2. Of the 392 unique records identified and screened, 24 (~6%) were included in the final review.

Table 5 shows the detailed extracted data for each article, and summarizes the technology types, hazards, study designs, main results, and advantages and disadvantages of the included studies.

3.2. Overview of intervention technologies

Interventions were categorized into three broad groups based on their primary purpose: (A) identifying and mitigating hazards during the construction planning phase (n = 9) [18-26]; (B) identifying and mitigating hazards during the construction execution phase (n = 11) [27–37]; and (C) worker health and safety training (n = 4) [38–41].

Hazard identification in the construction planning phase involved several distinct technologies: BIM-based rule-checking to identify hazards (n = 3) [18–20], automated task and site planning (n = 4)[21-24], and semantic algorithms that check safety plans for regulatory compliance (n = 2) [25,26]. Hazard identification in the construction execution phase was dominated by location-based tracking of workers to monitor location linked to a real-time site map (n = 5) [31–35] and alerting measures (n = 6) to signal hazard zones [27–30], heat stress [36], or harmful gasses [37].

Table 1
Conceptual groups of key terms (title, keyword, abstract) used for systematic literature search.

Construction	OHS	Digital technology	Intervention
“Construction industr*" OR “Construction sector” OR “Construction firm*" OR “Construction site” OR “Construction project” OR “Building design” OR “Real estate asset” OR Renovation OR Demolition OR “Facilit* management” OR “Architecture Engineering Construction” OR (design w/1 construct*) OR (engineer* w/1 construct*)	OHS OR OSH OR “Occupational health” OR “Occupational safety” OR “Safety management” OR “Accident prevention” OR Ergonom* OR Injur* OR “Industrial Accident” OR “Work Safety” OR “Work environment"	Digital* OR “Information technology” OR Software OR ICT OR (information w/1 “communication technology")	“Process evaluation” OR Implement* OR “Case stud*" OR “Test bed” OR “Pilot stud*" OR “Field stud*" OR “quantitative stud*" OR BIM OR “building information model*”

Table 2
Operationalized screening questions for inclusion and exclusion criteria in a systematic mapping review of digital OHS interventions in construction.

Inclusion Question (answer must be yes)	Definition
Is the article peer-reviewed?	Article must be from a peer-reviewed journal or conference proceeding.
Is the article available in full-text?	Full-text is available for review (e.g. download or interlibrary loan)
Is the article available in English?	Full-text must be available in English language.
Is the article a primary research article?	Reports on an original study with data collection and analysis. Cross-sectional, longitudinal, and case study designs were acceptable. No editorials, reviews, protocols, or letters were included.
Does the article report on an OHS intervention?	Interventions must be designed to directly reduce the risk of workplace exposures to hazards, and ultimately prevent occupational illness and/or traumatic injury. Interventions that only quantified risk without a proposed mechanism to reduce it were not included.
Does the article report on a digital intervention?	Interventions involve the application of digital communication, location-tracking, hazard identification, or training tools to achieve OHS goals.
Does the article relate to construction workers?	Hazard and risk reduction is intended for those onsite workers who are directly involved construction, renovation, or demolition activities for residential, commercial, and infrastructure projects. Long-term structural stability and safety of eventual building occupants is not included.
Does the article report on a worksite trial?	Interventions were tested with a real-world construction project via a pilots, test-beds, long- or short-term experiments and onsite simulations in the planning stage were all acceptable. Development of a conceptual framework, ontology, theoretical model or software platform without testing in a real-life construction scenario is not included.

Table 3
Data extraction categories and description of extracted information.

Category	Description of Extracted Information
Basic study information	- Reference (e.g. Melzner et al., 2013) - Hazards targeted (e.g. working at a height, or noise exposure)
Intervention characteristics	- Type of technology (e.g. rule-checking algorithm) - Intervention mechanism (e.g. identify structural openings workers could fall through)
Hazards targeted	- Exposures, hazards, injuries or illnesses the intervention aims to prevent (e.g. falls and related injuries/fatalities)
Evaluation context & methods	- Country of study (e.g. USA, or Germany) - Evaluation context & construction phase (e.g. construction execution phase of a high-rise commercial building) - Study design and sample (e.g. case study with 5 OHS professionals, or 17 workers) - Data collection methods and outcome metrics (e.g. number of hazardous openings detected by algorithm vs OHS professionals)
Summary of results	- Quantitative results of trial (e.g. statistics related to outcome metrics) - Summative results of trial according to authors (e.g. qualitative success rating of the intervention)
Conclusions	- Intervention advantages (e.g. potential to flag and fix hazards much faster) - Intervention limitations (e.g. sensors need to be reconfigured as project progresses)

Table 4
Summary of criteria for study quality assessment.

Quality Rating	Criteria for Quality ranking
High	- Clear description of the intervention technology - Explicit description of study design, basis of comparison, and the criteria for success - Explicit description of how trial data were collected and analyzed - Clear presentation of quantitative results wrt the a priori study goal - Fulsome reflection on limitations and strengths of the study
Medium	- Clear description of the intervention technology - Some description of (at least 3) o Clear description of the intervention technology o Description of study design, basis of comparison, and the criteria for success o How trial data were collected and analyzed o Clear presentation of quantitative results wrt the a priori study goal o Reflection on limitations and strengths of the study
Low	- Missing all or most of: o Clear description of the intervention technology o Description of study design, basis of comparison, and the criteria for success o How trial data were collected and analyzed o Clear presentation of quantitative results wrt a priori study goal o Reflection on limitations and strengths of the study

Worker training solutions were evident for both onsite (n = 2)[38,39] and offsite (n = 2) [40,41] applications. Onsite training used location-based worker tracking as performance feedback for workers instructed to avoid hazards [42] and on-demand video training via QR codes located on the worksite [39]. Offsite interventions included VR training and self-directed multi-media training about hazards [41] and safe practices prior to coming to the worksite or prior to starting work [40].

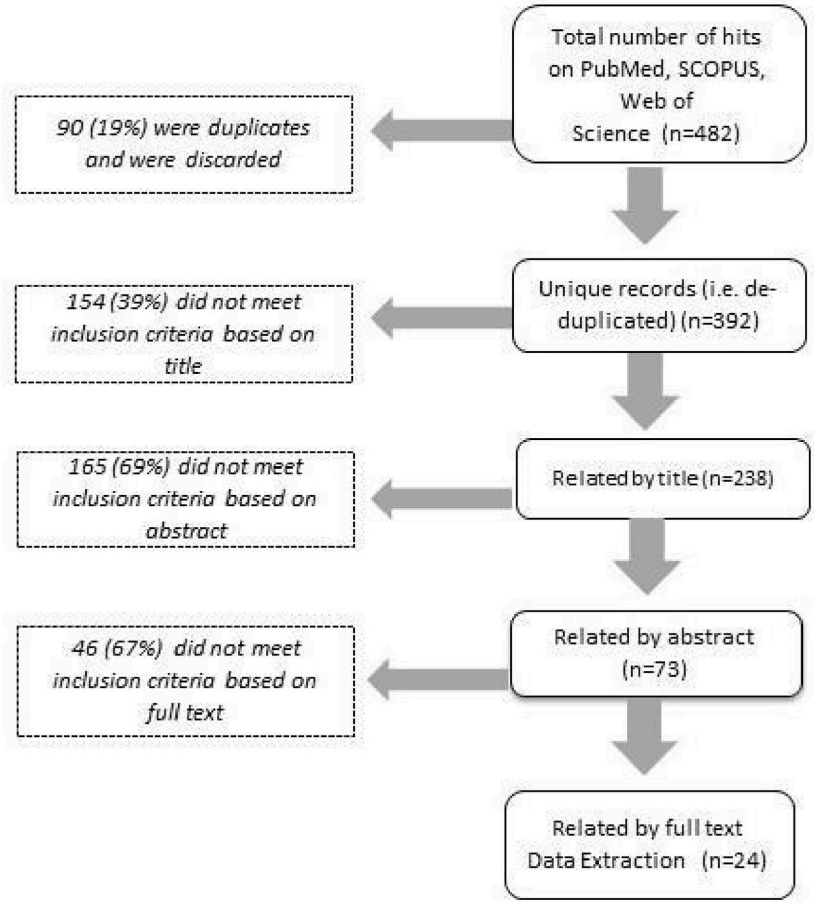

Fig. 2. PRISMA diagram illustrating the results of the systematic screening process for a literature review of digital OHS interventions in construction.

3.3. *Overview of targeted hazards and study designs*

Articles varied in the range of hazards addressed. Some articles explicitly named a broad scope or multiple hazards, while three did not name any specific hazards. The most common hazards cited were falls from a height or same level (n = 7), location-based unauthorized access to hazard zones (n = 5), unspecified location-based hazards (n = 5), and being struck by falling objects or machinery (n = 4). Electrical hazards and chemical exposures were each named in 3 articles. More rarely was risk for occupational illnesses considered, for example heat stress (n = 1), noise-induced hearing loss (n = 2) and musculoskeletal disorders from manual handling (n = 2). Note that this summary tallies each type of hazard named; since some articles named more than one the sum is greater than the 24 articles included in this review.

The hazards addressed in the included articles are largely consistent with the hazards identified as problematic in the construction industry, although frequency of targeted hazards does not seem proportional to injury statistics. In 2021 for example, 23% of construction injuries were due to falls, 19% were due to physical strain, 18% due to loss of control over handtools, and 11% due to structural failures such as cave-ins or collapsing scaffolding or other building materials [43]. It would appear that current digital OHS interventions are targeting meaningful OHS issues in construction, although the greatest efforts may be skewed toward cases with high immediacy and severity (i.e. falls from height, collisions) rather than cases with the highest incidence rates (i.e. musculoskeletal disorders and handtool events).

Study designs were largely described as feasibility or pilot studies without comparison or validation. Rarely were there validation studies based on a ‘gold standard’ such as expert review or concurrent measurement with a standard method. Evaluation methods were rarely described in full detail, and often not contained in the methods section at all. Methods generally focused on the development of the technology with evaluation more of an afterthought; oftentimes the evaluation methods were reported alongside the results or even in the discussion. Evaluations largely described feasibility of the technology’s basic functioning under real working conditions; health and safety consequences or the process of realistic practitioner-led implementations on active worksites were rarely reported.

3.4. *State of the evidence*

The weight of evidence considers both number and type of studies supplying evidence of an intervention’s effectiveness. In

Table 5
Summary of digital interventions for occupational health and safety in construction as proposed by the **24** reviewed scientific articles.

Reference	Intervention type	Hazard target(s)	Evaluation context & method *country, building type, sample size, participant type, metric what is the outcome being measured?s*	Summary of results	Intervention advantages	Intervention limitations
Construction planning stage interventions						
Melzner et al., 2013 [18]	BIM-based OHS rule-checking for construction planning; algorithm linked to BIM; checks geometric attributes directly in Industry Foundation Classes (IFC)-based BIM rule-checking platform.	Falls from height	Feasibility case study implements the rule-checking platform on a high-rise building project. Fall protection regulations from both the USA and Germany are applied and tested on the real building through simulations.	The case study shows that BIM can effectively aid traditional safety decision-making for fall protection equipment, while visualizing safety information highlights differences in results with country-specific regulations.	Leveraging BIM technology, this approach can aid the construction safety planning workflow and improve safety comprehension during the project's design and planning phases	Research is needed to enhance organizational aspects (e.g., integrating safety and BIM in early design and construction phases) and technical aspects (e.g., integrating IFC) in construction.
Khan et al., 2019 [20]	BIM-based rule-checking for construction planning Algorithmic modeling tools and BIM technologies.	Unauthorized entry and 'major' risks such as cave-ins, fall, safety egress.	Case study: By employing visual programming language (VPL), rules-based algorithms were created in commercial software to generate geometric conditions, visualize risks, install safety resources, quantify take-off, and optimize locations within BIM. Limited methodological details.	The case study testing on building foundation excavation demonstrated that the BIM-based system supports advanced and comprehensive safety planning for excavation pits and trenches, successfully designing slopes to prevent cave-ins per OSHA guidelines.	The potential of the VPL and BIM for the excavation safety planning and modeling at the pre-construction stage has been ascertained and confirmed with a real case study.	Not discussed, but potential future developments of the system are suggested.
Kim et al., 2016 [19]	BIM-based rule-checking for construction planning; algorithms for scaffolding safety integrated into BIM to augment safety managers	Falls from height, falling objects, electrocution, spatial conflicts, & scaffolding failure	Pilot comparisons of safety hazards identified by the prototype and by a panel of safety managers who recalled hazards after walkthroughs. No quantification, mainly informal qualitative analysis	Prototype identified hazards that the safety managers did not, though managers agreed that hazards could arise depending on the construction methods.	Production-linked planning of scaffolding has potential for economic and efficiency benefits beyond hazard identification	Method is labour intensive, and currently only applies to masonry scaffolding.
Elbeltagi et al., 2004 [21]	Automated Task and Site planning using spreadsheet-based scheduling macros to plan material delivery areas, temporary facilities, and safety zones	Falling objects, manual materials handling, and poor hand hygiene.	Case series at a multi-story, multi-phase hospital project with 3 main buildings in Egypt. Building phase 1 received no special planning. For phase 2 the tool was used to plan temporary facilities was done for temp facilities. Layout efficiency index was the main quantitative method, alongside qualitative observation.	Layout scores reported only for the new solutions, no quantitative comparisons made. Anecdotally, phase 1 experienced difficulties with disorganization and manual handling workload problems. Unplanned material storage areas and crane placement resulted in excessive material waste and handling costs, and	None presented	None presented

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Table 5 (*continued*)

Reference	Intervention type	Hazard target(s)	Evaluation context & method *country, building type, sample size, participant type, metric what is the outcome being measured?s*	Summary of results	Intervention advantages	Intervention limitations
				less maneuverability within the site.		
Kim et al., 2018 [22]	Automated Task and Site planning using 4D-BIM	General hazards related to temporary structures	In the decision-making process, a total of 256 scaffolding plans were automatically created based on user input. In addition to the quantitative evaluation, professional judgement of the construction managers was used to assess the constructability and effectiveness of the plans.	The system can be utilized as a decision-support system that enables the users to develop a plan with minimized safety hazards related to scaffolding hile considering workflow, cost, and duration at the same time.	The decision support system provides safety plans for temporary structures considering their costs and durations. The system automatically generates multiple scaffolding plans and quantitatively evaluates them regarding safety, cost, and duration.	None presented
Rozenfeld et al., 2009 [23]	Automated Task and Site planning with 'Construction Hazard Assessment with Spatial and Temporal Exposure (CHASTE)' forecasting software coordinates timing of activities to reduce exposure to adjacent teams.	Safety risks (especially loss of control events) as well as noise and dust.	Feasibility pilot in 2 stages without living participants; no basis for comparison. First pilot: 6 months of archived data for 8 activity types were analyzed from a seven-story residential building with 3000m2 floor area, calculating 5424 possible accident scenarios. Second pilot: 45 840 possible accident scenarios generated for the construction of high-tech labs and offices for a semiconductor company.	63% of scenarios impacted crews and workers other than those generating the hazard. No comments on the accuracy of the hazard identification.	Potential to be highly automated, efficient, and allow for better planning and integration of tasks	Unclear the degree to which predicted safety risk levels correlate with safety performance. Without onsite implementation, it is unclear what practical impacts the tool could have on safety in construction management.
Golabchi et al., 2015 [24]	Automated Task and Site planning with RULA and REBA ergonomic tools into a 3D virtual model of the work environment to identify hazards and trigger redesign.	Musculoskeletal disorders from manual work	Feasibility pilot: 3D model was developed for a modular construction pre-fabrication facility in Canada, with simulated workers/ work tasks. Automated model analysis compared to expert manual analysis of the physical site. Comparisons also made to re-designed simulations to test potential interventions.	Authors state that feasibility goals were met: to demonstrate efficacy. Degree of fidelity with expert analysis and improvement with re-design is not quantified.	Automated analysis is faster; potential for re-designs to increase productivity and work quality of redesigned work stations. Not mentioned: proactive primary prevention	Significant time and effort needed to develop 3D model and populate it with site and task data.

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Table 5 (*continued*)

Reference	Intervention type	Hazard target(s)	Evaluation context & method *country, building type, sample size, participant type, metric what is the outcome being measured?s*	Summary of results	Intervention advantages	Intervention limitations
Li et al., 2022 [25]	Semantic algorithms to check compliance of safety plans with 'SafeConDM', which proposes regulation-based solutions when fall hazards are identified	Falls from height, struck by, scaffolding, slips and trips, caught-in between, electrocution	Plausibility test of tool on the IFC models of 3 cases in Germany and Denmark. Listed outcomes were computational time, "correctness" and "completeness" in terms of fidelity with hazard locations identified by a construction safety engineer. Authors state that evaluation was not "a rigorous, systematic assessment" but rather a tool for iterative development of the tool.	Quantitative correctness and completeness metrics are not given. Numbers detected by technology are given, but the correct (engineer-identified') numbers are not given, so it is not possible to calculate post hoc. Authors note that "numerous fall hazard spaces were identified that we had not predicted"	None presented, though processing time and computational cost are implied in the rationale	None presented, though future work names expansion to more hazards.
Martinez-Rojas et al., 2020 [26]	Semantic algorithms to check compliance of safety plans with natural language programming to detect deficits and facilitate correction	Broad range of safety hazards related to concrete work	Validation trial: Expert ranking ('gold standard') compared 25 safety plans checked by the automated tool; outcome is the deviation between the automatic output and the expert review, with a point-ranking system quantifying correct/incorrect. No onsite safety metrics are investigated, nor are communication streams or implementation challenges.	Correctly identified required information for five of the seven safety plan topics, while 2 topics showed greater differences. aöthough the # of incorrect plans is higher, the average deviation is lower than in other items, such as item 2 or 3. In 20% plans additional information was identified with low deviation from expert. In 80% of plans, some information was not identified, with 3 times the deviations.	Automating would be a cheaper and faster method, with potential to assist with updates throughout the project.	Only covers concrete structures. Identifying key features in the text does not assess the quality of the plans. Freer text remains challenging to assess; conventional spellings required. No onsite safety metrics investigated
Worker Training						
Zhao et al., 2013 [40]	Pre-work, offsite virtual reality based training	Electrical safety risks	Pilot study: VR-integrated safety training program was developed and adopted in a construction project in the U.S. Limited methodological details.	The analysis found that large portion of the occupational fatalities and injuries were related to workers' unsafe acts and lack of awareness on the safety hazards.	A pilot application which used virtual reality technology in the safety training was demonstrated to help to set up the safety culture in workers' daily practices, and ultimately to mitigate the safety risks in construction projects.	The description how the study was conducted and evidences for the results are lacking. None described

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Table 5 (*continued*)

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Hare et al., 2020 [41]	Pre-work, offsite training with multi-media digital tool to educate designers on typical design-related hazards.	General, unspecified hazards	Randomized trial: 40 novice and experienced designers were split evenly between control group and a group using the prototype tool. Both groups assessed fictitious Computer Aided Design (CAD) drawings, number of identified hazards were compared between groups.	The results showed all experimental groups outperformed control groups, with the novice groups demonstrating the greatest increase in both hazards spotted and quality of alternative options recommended. The increase in mean hazards identified in the experimental group proved statistically significant	The overall results clearly demonstrate that use of the multi-media digital tool leads to improved hazard identification, in terms of number and scope of hazards.	Mention data access as a bottleneck.
Li et al., 2015 [42]	Onsite training with location-tracking during hands-on training used to signal hazards and deliver feedback on performance	Falls from height and struck-by incidents while hoisting prefabricated components.	Pre-post comparison study: 10 workers underwent training for precast facade installation on 40-storey public housing blocks in Hong Kong. Training involved safety and practical aspects of installation of temporary inclined bracing, fixing fabric reinforcement, hoisting and positioning modules. Baseline and post-training comparisons were made of: 1) time to complete tasks, 2) number of warnings and hazard alerts, & 3) worker feedback).	Productivity gains (time to complete tasks) was not quantified, just that hazards were detected and timely alerts provided to workers. Worker feedback: 75% of workers reported feeling the alerts could increase safety, 80% thought the digital training was superior to traditional.	Potential for faster skills acquisition through vivid visualization and quantitative feedback, real-time proactive hazard warning, automated accident and incident reporting, visualization can be used to augment off-site training that does not impeded production.	Worker acceptance issues: privacy and personal autonomy; 20% of workers thought RF could harm their health; 'some' thought the locator tags on their helmets presented a safety risk. 'Some' believed safety always clashes with efficiency. Visualization has limited realism; tracking is limited in complex building sites; does not cover non-location-based hazards. Not mentioned: risk of 'blame game' in post-incident investigations
Edirisnghe et al., 2016 [39]	Onsite training with on-demand QR-based mobile phone access to safe work training videos and safety information	General location-based hazards	Case studies at 2organizations in Australia. Assessed with in-depth interviews of safety managers and workers involved in system implementation and quantification of engagement with the informational videos	In one organization, the introduction of the CodeSafe system coincided with a reduction in injury rates, though this cannot be concluded as causal. Workers involved in making the films believed films would be an effective communication tool.	Safety information is delivered on-demand to where the work is taking place	Barriers to implementation of the technology include workers' reluctance to use personal smart phones, limited internet connectivity, and organizational and national regulations on mobile phone use on construction sites
During construction work						
Lin et al., 2013 [31]	*Worker* Location-tracking (BLE, GPS, etc.) integrated	Unauthorized entry	Feasibility field trial: on an unknown number of workers at a dam	The study resulted in the following areas for management use: (1) dam construction	Described as an effective and efficient information system	None presented. Note that proposed system might raise

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Table 5 (*continued*)

Reference	Intervention type	Hazard target(s)	Evaluation context & method *country, building type, sample size, participant type, metric what is the outcome being measured?s*	Summary of results	Intervention advantages	Intervention limitations
	with 3D digital model (BIM)		construction site in China. Presumed qualitative assessment of which features are used, and useful.	worker behavior, (2) online real-time monitoring over the whole work area, (3) an evaluation system for early warning and forecasting refinement for the owners of construction quality and worker safety management, (4) rapid response to any quality and safety problems, (5) effective control of safety and quality, and (6) the implementation of worker behaviour analysis following the acquisition of the real-time monitoring data.	to evaluate worker behaviour and support decision making in real time.	issues on workers' integrity.
Park et al., 2017 [32]	*Worker* Location-tracking (BLE, GPS, etc.) integrated with 3D digital model (BIM) intended to facilitate safety supervision	Unauthorized entry into physical and chemical hazard areas	Field trials with 4 participants over multiple scenarios to quantify the potential safety hazards identified on the second floor of an indoor construction site: 1) initial test to map fidelity of signal location 2)7 hazards scenarios repeated 10 times by each of 4 participants, designed to test hazards, false alarms, and sensitivity of near-contacts.	Sensitivity of hazard detection was 97–100%. Specificity of hazard detection ranged from 7.5 to 100%, indicating that false positives can be quite common in some scenarios.	None presented	Performance relies on geometric accuracy of BIM and hazard areas, which can change with ongoing construction. Bluetooth beacons needed every 5 m. Poor specificity will result in a lot of false alarms. Not mentioned: personal autonomy/privacy issues
Naticchia et al., 2013 [33]	*Worker* Location-tracking integrated with 3D digital model (BIM); provides alerts when workers access a forbidden area	Unauthorized entry	Feasibility pilot: 3 workers performed quasi-experimental tests in a real worksite: 1) walking through potentially hidden spots in a single area to test positional accuracy; 2) intrusion test to signal unauthorized access over 2 work areas. Compared observed work positions to those visualized on the site map, quantified visualization delay, and recorded if/	No quantitative results presented. Trial 1 conclusions were based on maps: "the system accurately matches the zone where the worker is operating". Trial 2: concluded that the "software worked well" for identifying workers present and alerting intrusions.	Trials appeared robust to low-density deployment and onsite obstacles; Non-invasive, quick and easy to install and expand/ reconfigure.	False alarms mentioned in discussion, but not in the trial results. Accuracy and precision is limited; tool appears to be accurate within zones but not to actual position. Not mentioned: privacy and autonomy for worker tracking.

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Table 5 (*continued*)

Reference	Intervention type	Hazard target(s)	Evaluation context & method *country, building type, sample size, participant type, metric what is the outcome being measured?s*	Summary of results	Intervention advantages	Intervention limitations
			when alerts registered.			
Kim et al., 2016 [34]	*Worker* Location-tracking integrated with 3D digital model (BIM), identifies potentially hazardous areas as the deviation between the BIM-derived optimal (shortest) route and workers' actual path	Location-based hazards such hazardous materials, bare electric wire, and falls	Validation trial at a 5-floor academic building in Korea: expert hazard identification ('gold standard') was compared to locations of hazards identified by the system. Time to complete the method, cost to complete the method, and method accuracy are listed as outcomes of interest. Number of workers and duration of test not specified.	Only the number and type of method-identified hazards is reported, along with the number of false positives. The system found 35 hazardous areas across the 4 floors, 80% were identified as real hazards by the expert. Cost and time not quantified, though RTLS set-up time, task duration and 'unmitigated hazard time' are mentioned as important.	Does not require active participation or reporting and does not impede productivity. Hazard flags are immediate, without delays as occur between or during walk-throughs.	Savings depend on economies of scale required. Hazards must be visible, perceived as hazards, and deemed important enough to alter worker behaviour. Iron forms can create magnetic field errors. Not mentioned: privacy and autonomy for worker tracking.
Lin et al., 2013 [35]	*Worker* Location-tracking (BLE, GPS, etc.) integrated with 3D digital model (BIM)	Not specified, presumed unauthorized entry	Feasibility field trial: 1 worker tracked while pouring concrete pillars during a 12-h night shift at a large hydroelectic dam in China. Specific data collection and analysis methods not explicitly described	Conclusions state that the method "offers an effective and efficient alternative to evaluate real-time employer's safety management." However, no metrics of effectiveness or efficiency are offered, and no basis for comparison is presented.	Battery-operated, small and solid sensors are easy to deploy and easy to reconfigure.	None mentioned; Consider privacy and autonomy for worker tracking.
Yang et al., 2022 [27]	Computer-vision hazard ID listing locations in BIM	Falls from height	Validation comparison: Dataset containing approximately 4000 images from multiple sources to detect on-site safety risks and train the deep learning model. Hazard identification from two safety officers (gold standard) and the automated system were compared.	Positive predictive value ranged from 68 to 96%; sensitivity ranged from 58 to 83%, though it was noted that there were some instances where the system identified hazards not first detected by the safety officers due to visual limitations.	Potential for more thorough and efficient hazard detections	Limited by the condition of the construction site, this case study is retrospective, and proposed for the preliminary verification of feasibility of this method. Not mentioned: privacy and autonomy for worker tracking.
Rey et al., 2021 [28]	Computer-vision hazard ID listing locations in BIM with unmanned aerial systems (drones) with system called Smart Inspecs.	General hazards	Case studies: implemented at 2 construction sites with 55 inspections. Evaluation conducted through document/email review, observation, participant interviews (n = 7)	Smart Inspecs system reduced on-site inspection time by 73% in comparison to standard means. Users reported positive impact in terms of information transparency and management utility.	Allows for more efficient inspection and identification of hazards.	Does not address applying the data to corrective actions.

(*continued on next page*)

Table 5 (*continued*)

Reference	Intervention type	Hazard target(s)	Evaluation context & method *country, building type, sample size, participant type, metric what is the outcome being measured?s*	Summary of results	Intervention advantages	Intervention limitations
			and worker survey (n = 63) (specific analysis details unspecified).	Faster correction of safety deficiencies was reported.		
Panuwatwanich et al., 2020 [30]	Location sensor-based auditory alarm system to warn of hazard zones called AmI	Falls from height, unauthorized entry, location-based hazards	Pre-Post comparison: one week with and without the AmI at a high-rise construction site in Thailand. Comparison based on hourly intrusion rates (count/worker).	Significant, 78% reduction in the number of intrusions in designated fall hazard zones in the week after the alarm system was activated	Workers get immediate feedback when passing into dangerous zones.	Workers may over time ignore the alarm. Long-term trials are still needed to assess alarm fatigue.
Yi et al., 2016 [36]	Physiological (heat stress) and location monitoring with integrated smart bracelet, GSM environmental sensors, mobile phone	Working in hot and humid environments	Feasibility field trials on 6 Hong Kong construction sites with 39 workers. Subjective heat strain ratings (RPE) were predicted using objective environmental data and heart rate resulting in 550 sets of synchronized work-related, environmental, and personal data. Correlation, mean absolute percentage error, and root-mean-square deviation were used to evaluate model performance.	Correlations ranged from 0.907 to 0.966, mean absolute percentage error from 0.814%, to 1.795%, and root mean square error from 0.565 to 1.024 RPE points.	Potential to deliver early warnings of heat-stress in real time based on wearable sensors and environmental monitoring.	One single sample source and limited sample size; participants were mainly steel bar bender and fixers. Not mentioned: privacy and autonomy for worker's personal data.
Cheung et al., 2018 [37]	Environmental (gas) sensors integrated with 3D digital model (BIM)	Hazardous gas, Unauthorized entry)	Feasibility trial at a tunnel construction site in Taiwan with three test types: (1) system performance for gas detection; (2) signal transmission and attenuation; (3) node interference.	The system successfully detects and reacts to hazardous gas at a distance of 300 m. Transmission distance in the tunnel can reach up to 250 m, or 450 m with a router. The signal was not significantly affected by high-speed ventilator or lift truck motor.	System has potential to be more effective and safe than handheld equipment for measuring gas levels.	System cost remains high. Suggestions of technology improvements are listed.
Sharmanov 2017 [29]	Submitted photos of hazards used to calculate 'security index', by BIM location	General hazards	Feasibility trial: an algorithmic security index developed from 11 hazard factors related to production.	Reported success in modelling whether the level of labor protection has increased; no quantitative data reported. No comparison or discussion of validity of index.	Allows estimation of hazard level, i.e. 'level of labor protection' over time.	None presented

aggregate, there were no solution types that met the standards of 'evidence of efficacy' as shown in Fig. 1, which requires two or more high-quality papers giving evidence that workplace exposures, injuries, or illnesses would be reduced under ideal or controlled conditions [9]. Only a few individual studies had the methodological quality and specifically quantified findings that might eventually contribute to such evidence [24,26,32,34,41,42].

Three broad categories of study design contribute evidence in on an increasing scale: (1) basic functionality and feasibility; (2) basic comparisons; and (3) quantification of impact. All studies reported functionality or feasibility of the tested technologies/systems to a lesser or greater extent, often with suggestions for how technology and systems can be improved. Basic comparisons included (often qualitative) comparisons between the digital OHS intervention's performance and that of a traditional method such as ratings or hazard identification by safety managers. The third category of quantifying impact contributes the most to the evidence maturity timeline, but was also the most rare. These studies compared OHS outcomes or metrics before and after an intervention, or between intervention groups. For example, Yi et al. [36] presented results about prediction of heat stress, Rey et al. reported reductions in safety inspection time with a digital method [28], and Hare et al. demonstrated improved hazard awareness after digital training [41]. In addition, Panuwatwanich et al. and Park et al., quantified reduction of unauthorized entry into physical [30] and chemical [32] hazard areas, respectively. As these studies are spread out across multiple digital technology types and hazard targets, the evidence for any one digital OHS intervention remains small.

In the present review, the number of studies per digital intervention type is limited between 1 and 5, lacking the accumulated minimum 4 articles and substantial supporting documentation required to recommend broad dissemination. Even when there are multiple studies on a specific intervention type, they have considerable heterogeneity in terms of how they implement the intervention, design the trials, quantify the outcomes, or summarize the results. As a consequence, there is not a weight of consistent and confirmatory evidence that any of these interventions are effective in real worksites. Despite the infrequent use of robust study designs and statistical comparisons, many of the articles nonetheless made conclusions about efficacy and effectiveness, with statements like 'the method successfully reduced hazards' or 'we conclude this method is effective in improving workplace safety'. A more skeptical interpretation would be that while the technology appears to function in a real worksite, many more high-quality studies quantifying the impact on exposure, injury, and illness are needed. It should be noted that the mere presence of multiple high-quality studies is not on its own sufficient to demonstrate that an intervention should proceed to dissemination. There is also a question of the *size* of the impact, the cost-benefit tradeoffs, and the feasibility of wide-spread implementation. In all likelihood, the proposed digital OHS interventions are not all suitable for wide-spread implementation. For example, some of the studies were more than 15 years old, and yet no follow-up studies were found to indicate that the initial proposal describing the technology development were implemented or had measured OHS impact.

Although effective intervention implementation is known to be a challenge in construction, the interventions' strengths and limitations relative to adoption were rarely discussed. On the contrary, discussion sections frequently highlighted the potential for big impact of digital systems and tools. Although limitations mostly concerned a need for further development of a digital system or tool, some methodological and practical limitations were named as well. For example: small sample sizes [36], workers' long-term behavior deviating from the short-term trial [30], barriers to using smartphones for accessing safety information onsite [39], industry competency gaps in analyzing generated OHS data [28], economies of scale [34], and worker knowledge limitations in identifying hazards [34]. Interestingly, other potential organizational and social barriers were not discussed, for example personal privacy and autonomy when tracking worker locations.

4. Discussion

This literature review aimed to systematically map the evidence base for digital OHS technologies in the construction industry in terms of the maturity of interventions along the continuum of development-efficacy-effectiveness-dissemination [9]. These aspects are discussed below insections regarding evidence maturity, and the remaining challenges to effective interventions. This literature review also aimed to identify any gaps in this evidence base, and to make recommendations for future work to address the gaps. The sections titled *Recommendations* highlights opportunities for both researchers and practitioners to contribute to the evidence base, and to make the most of the information available now. Finally, this section ends with consideration of the *Strengths and limitations* and a *Conclusions* section that summarizes the main findings relative to the aims.

4.1. Evidence maturity: still in the first stages

Although some digital OHS interventions had more studies and/or moderately-higher quality, in general the evidence level remains in the development and efficacy stages, with no evidence of effectiveness or to support wide-spread dissemination. If one conceptualizes the journey from 'idea' to 'full-scale implementation', there is an intuitive order to the type of study conducted, starting with smaller feasibility pilots that contribute to improving the intervention design. Then come validation studies which compare novel risk assessment tools to 'gold standards' and pre-post trials to estimate the impact of the solution. Controlled experiments to quantify the impact under ideal conditions would give way to larger-scale, long-term trials which evaluate the primary outcomes as well as implementation barriers and success factors.

Considering length of this 'journey', most of the 24 included studies were at the beginning, characterized by feasibility trials, tests of simulated work, or small pilots. Not all interventions will complete the journey. For example, some technologies may be promising, but still have not been implemented even with several years between initial development and the present day. In 2009 Rozenfeld et al. reported development of 'CHASTE' forecasting software to plan construction activities and reduce hazardous exposures of adjacent teams by integrating data from Microsoft Project, Microsoft Access and AutoCAD [23]; there have been no reports of its implementation or effectiveness in the 1.5 decades since.

4.2. Overcoming the challenge: digital competence barriers to successful adoption

Developers of digital OHS solutions are innovating state-of-the-art technologies, but there remains a gap between what could be done technically and what is demonstrated to be successful on real construction sites. In a recent study of BIM opportunities for OHS, industry stakeholders described barriers to success including risk aversion, lagging technical skill, and interfacing barriers presented by a lack of standardization across platforms and approaches [5]. The notion of digital competency gaps on the construction site in analyzing and interpreting digital OHS data was likewise mentioned by Rey et al. in one of the included studies [28]. The result is a gap between the R&D efforts that are expanding possibilities and the actual implementation in a way that successfully reduces injury and illness among construction workers. Nanji et al. identified five individual factors reported by construction stakeholders as influencing the adoption of safety technologies, including the level of training and technical support required/available, as well as the complexity of the technology [44]. It is perhaps meaningful that in smaller construction companies and workers with less experience are less likely to prioritize technology factors as potentially limiting or influencing the adoption of safety technologies in construction [44]; an element of 'not knowing what you don't know' when it comes to adopting novel technologies can hamper successful implementation and effective use. Digital competence is a dynamic property that will likely increase over time; more research is needed to understand how digital intervention implementation can be matched with the capacity of current workplaces.

4.3. Overcoming the challenge: privacy and autonomy barriers to successful adoption

Many of the articles included in the review focus on opportunities for technical development, without great focus on the application context or what will be needed to fully integrate the technology into practice. As a notable example, eight of the included papers employed some type of worker location tracking [27–35]., and the ubiquity of wearable sensors would suggest more growth in this arena. However, the privacy and autonomy issues of worker location tracking went largely unmentioned in the publications. Focus groups with construction industry stakeholders in Sweden suggests that there is substantial resistance from labour to continuous, personally-linked tracking of workers' location [5]. A study of 120 construction workers from three different sites in the USA found perceived privacy risk was associated with intention to adopt wearable worker location-tracking technologies, along with social influence and perceived usefulness [45]. Although it may not be relevant in every social context, real-life implementation in many regions and contexts is likely to give rise to objections from labour and perhaps regulators. Successful implementation in real construction settings may rely on different contextual and organizational pre-requisites than reported by the included development studies. This is an area which needs further study.

4.4. Overcoming the challenge: longevity barriers to successful adoption

Even when efficacy seems strong, a longer-term effectiveness study can demonstrate the weakness of an intervention. For example, Panuwatwanich et al. describe even when initial implementation of a hazard warning system appears to reduce intrusions into a hazardous zone, over the long term alarm fatigue can reduce the effectiveness [30]. Similarly, an intervention might work under controlled conditions with researcher oversight, but that does not imply it will be effectively adopted in an organisation with poor safety systems or safety culture [46]. Indeed, 'organizational culture' was one of 12 highly influential predictors of safety technology adoption in construction, and the only one to emerge from the category of management and organizational factors [44]. True long-term effectiveness thrives in a context that embraces and accepts safety reminders and information to effectively act on them. In contrast, a safety culture which is motivated to defeat safety procedures is likely to defeat even the most advanced digital technologies.

Cost and value for investment (both in terms of currency and time/effort) is consistently listed as a pre-requisite to technology adoption [44,45,47]. As part of developing the model for safety technology adoption predictors in construction, a survey of 337 construction personnel identified the technology factors of reliability, effectiveness, and durability as the three most influential predictors of safety technology adoption [44]. However, maintaining reliability and durability in a sector which has been lagging in technical competence is not a trivial objective, and will require investment and capacity building. Adopting an unproven intervention requires a greater comfort with experimental, longer-term, and iterative shifts in business practice [48], which may not characterize most construction enterprises. This is consistent with the Extended Unified Theory of Technology Acceptance [47], where technology use behaviour is determined by a combination of habit, intention and facilitating conditions, which is in turn impacted by expectations around performance and effort, social influence, and price value. How digital OHS interventions are impacted by habituation, organizational safety culture and innovation-risk aversion is an important topic for future research.

4.5. Overcoming the challenge: conflicting logics and valuing evidence

Promises of future benefits from new technology is not enough to spur investment in in a low-margin sector like construction [4]. Rather, there is a strong incentive to see immediate benefits on digital and safety investments [49,50]. Jacobsson et al. suggest that the need to see immediate benefits is not only based on the individual technology user's perceptions, it is built into the underlying structures in the context where contractor firms are operating [51]. The construction industry is entangled in a *project-logic*, emphasizing that the project should finish on time and budget. This implies that all initiatives that could be seen as a threat to keeping budget and deadlines for a project will be rejected, unless separate resources are allocated for testing and developing digital tools in general and for OHS [49,52]. The Evidence Maturity Timeline in Fig. 1 is governed by a different *public health-logic*, emphasizing rigorous trials and evaluations in different steps over time when a new intervention should be developed, tested, evaluated and finally implemented into practice. Thus, we have to reconcile two conflicting logics. For the construction industry to approach something that looks like Evidence Maturity Timeline when developing and testing digital tools for OHS, it needs to be prioritized on the top management's agenda. This would include setting aside resources for testing digital tools for OHS and incorporating them as an integrated part of the company's business logic that that goes far beyond the duration of the single project. Future intervention development needs to consider the industrial context of the construction sector, and formulate an appealing value proposition with respect to costs and benefits.

5. Recommendations

To have a broad impact on construction health and safety, the current evidence base will need to evolve towards supporting dissemination. However, the current evidence is mainly focused on development, with some steps towards efficacy. To expand the evidence for efficacy, there is a need to focus on stronger study designs and more thorough analysis of qualitative, and especially quantitative, outcomes. It should be acknowledged that this type of research is costly, and the interventions represent substantial investment on the part of construction firms. To motivate that investment, efficacy studies must provide more quantitative evidence that the proposed methods have the capacity and potential to act on hazards and health outcomes in the workplace. Maturing towards 'evidence of effectiveness' will require contribution from both researchers and industry stakeholders to address implementation challenges beyond what gets tested in a lab: worker preferences, social desirability, organizational readiness and skills capacity for implementation [5,44]. Randomized controlled trials with real workers may be challenging-to-unfeasible in terms of resources, but research reports on this topic need to have more clearly-defined test protocols with explicitly stated goals, study parameters, and measured outcomes, data collection methods for the study outcomes, and conventional analysis and interpretation. Recommendations for developing these programs of research are described in Table 6.

In addition to these recommendations for researchers, industry stakeholders can also contribute to developing evidence maturity by shifting industry perspectives around how 'evidence' is valued and pursued in digital OHS for construction. Subject area conventions from construction (orthodoxy-driven) and ICT (R&D focused) do not include the same evidence weighing practices that exist for example, in medicine and health sciences. The appetite for evidence can extend towards active collaboration in research, where industry stakeholders participate actively in pilots, trials, testbeds, including giving critical feedback. Still, until the evidence base becomes stronger, industry would do well to approach untested or under-tested technologies with caution; in the best case this results in a balance between open mindedness (which is required for a successful shift towards digitalization) and skepticism that manifests as an appetite for evidence.

6. Strengths and limitations

This article analyzed the literature pertaining to digital OHS interventions in the construction industry using an Evidence Maturity Framework; giving a unique perspective on a growing area of research. While this systematic mapping review appears to be the first to analyze the digital OHS intervention evidence in this way, it also has some limitations. All the included articles were written in English; while this is often the de facto language of published academic literature, there are likely to be peer-reviewed literature in other languages that were not included. Peer-reviewed scientific articles and conference proceedings are an important avenue for relaying evaluations of novel interventions. However, in the rapidly-evolving arena of digital technology, the contributions of many private sector and commercial R&D are not peer-reviewed, despite potentially evaluating field implementations. 'Peer-review' was the minimum quality rating set for inclusion in this review, but it likely reduced the number of emerging technologies that might be found in grey literature or commercial and trade publications. Publication bias is another limitation faced by all reviews that is especially relevant here; the interventions that are not found to be efficacious or found to produce no measureable improvements in outcomes. The impossibility of inclusion of these in the reviews tends to overestimate the success of interventions overall.

7. Conclusions

This systematic mapping review evaluated the state of the evidence for digital OHS interventions in construction. Most of the 24 papers identified during our systematic search and included in this review provide a low to no evidence that digital OHS interventions prevent injury and illness, or that they improve health and safety conditions for construction workers. In aggregate, this topic area is characterized by rapid innovation and iterative development, but a long way from strong and consistent evidence that any of the digital solutions described have a demonstrated efficacy or effectiveness when implemented under real-world conditions. This gap can partly be explained, with a few exceptions, by a technocentric perspective focusing on technology's feasibility for potential applications. There is little reflection over potential challenges tested applications may encounter if they would be integrated into current and future work practices. However, even if research would follow our recommendations and change perspective towards building evidence maturity, there is a conflicting logic between an evidence maturity framework and the project logic governing construction practice. The evidence maturity framework has an inbuilt logic that results are achieved by step-by-step in a longitudinal process, whereas the project logic rewards methods that show quick and clear results here and now. Thus, there are challenges in achieving wide-spread adoption of digital OHS-applications where real-world implementation has been demonstrated to be both effective for OHS outcomes and feasible relative to financial, time, and human resources. Apart from continuing testing digital applications' feasibility for digital OHS-interventions, future research needs to focus on how the logic of an evidence maturity-inspired framework can be aligned with a project logic. This is, research has to provide evidence step-by-step to construction practice by explaining how results here and now can contribute to improved OHS, but researchers need to enhance the understanding among construction practitioners how OHS can be improved by digital OHS-applications. This path forward can be facilitated by multi-disciplinary approaches and methodologies, and perspectives from a wider group of stakeholders, which can facilitate the management of the tensions

Table 6
Recommendations for researchers to improve the evidence base for digital occupational health and safety interventions in construction.

Recommendations for Future Research
Research Topics
• Develop and evaluate strategies that match with the current capacities of construction workplaces; consider technology complexity and support needs during design and requirements for digital capacity building during implementation
• The impact of cultural and context-specific worker acceptance factors need to be rigorously evaluated to 'stress test' potential interventions to the challenges of worksite use. Privacy and autonomy concerns, but also usability issues are very important for location tracking and wearable sensors.
• Potential unintended consequences and novel hazards should be explicitly sought and investigated.
• Organizational readiness in terms of culture and orientation towards safety, change, and digitalization should be considered when selecting implementation sites and reported when sharing results.
• Economic factors and return on investment should be evaluated for promising interventions meet the efficacy standard. Technology costs continue to go down for implementation, but costs should be considered more widely to include maintenance, reconfiguration, training (with worker turnover), technical support, and in-house capacity development.
• Select outcomes that more closely represent the ultimate injury and illness prevention goal of the digital OHS technologies: reduction of exposures, rates of injury and illness
Methods and Reporting Approaches
● Consider more experimental study designs with control groups, or at minimum, robust pre-post comparisons.
● Include clear descriptions of the primary intervention outcomes, and how related data is collected, and the recruitment and characteristics of study participants
● Report methods and results for statistical analysis and inferential tests. For example, measurement validity can be quantified by comparing the novel tool to a gold standard and reporting sensitivity, specificity, and ROC curve
● Incorporate robust intervention evaluation methodologies from the health sciences, including clinical validation methods, experimental trials, and cohort studies.
● Incorporate process evaluation methods from implementation science, since some of the real barriers to successful implementation are not merely digital design aspects, but related to the socio-technical systems comprising a workplace.
● Include more construction stakeholders in the development of interventions to better understand the construction context and specify requirements, as well as to develop meaningful test scenarios.
● Since a greater focus on health and safety outcomes could be limited by over-reliance on technical perspectives, multi-disciplinary teams and projects that include the perspectives of OHS practitioners and public health researchers is desirable.

between an evidence-based way of thinking and a project-based way of thinking.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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