RESEARCH PAPER

Wearable Sensor and Exoskeleton Interventions for MSD Prevention: A Scoping Review of Implementation Barriers

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Abstract

Background: Work-related musculoskeletal disorders (WMSDs) are still one of the most prevalent causes of disability and lost productive time worldwide and manual material handling, awkward postures, and repetitive tasks are still the main contributors to the incidence of WMSDs in the construction, healthcare, manufacturing, agriculture, and logistics sectors [1–6]. Promising passive and active exoskeletons are developed and validated wearable inertial, electromyographic and pressure sensors. Despite the demonstrated efficacy in the laboratory, however, its uptake in the real world has been poor, and the reasons for this implementation gap are distributed throughout the engineering, occupational-health, and human-factors and organisational-behaviour literatures.

Objective: The aim of this scoping review is to characterise the scope, range and type of published evidence on the barriers (and, if reported, facilitators) to the implementation of wearable sensors and exoskeletons in the real world for MSD prevention in occupational settings.

Methods: The review was conducted within the framework of Arksey and O'Malley as modified by Peters et al. from the Joanna Briggs Institute (JBI) and reported according to PRISMA Extension for Scoping Reviews (PRISMA-ScR) [1–3]. To identify the literature, a Population–Concept–Context (PCC) question was structured and then searched across multiple literature aggregators in biomedical, engineering, and occupational-safety literature. An initial search yielded 135 entries; after de-duplication of cross-indexed entries, 74 sources survived and 52 of these were found to meet the inclusion criteria and were charted.

Results: Issues around wearable sensors fell into five themes technical/environmental reliability, cost/return-on-investment, data governance and privacy (the constant 'surveillance' and 'big brother' problem), user comfort and usability, and organisational/regulatory immaturity [7,9–23]. Biomechanical discomfort and anthropometric fit (24–36); task and environment compatibility (38–41); psychosocial and identity-related resistance (24–36); cost/financing (24–36); and the lack of mature selection and certification programs (37–41) were all grouped together as barriers, but within distinct domains. The facilitators discussed the key elements of worker participation in design and piloting, visible leadership support, a phased and voluntary roll-out, and a longitudinal field evaluation.

Conclusion: Technology families are ergonomically promising and under implemented within the organisations. The level of progress will be less about additional device development and more about the implementation-science-informed rollout plans, inclusion of body size and gender in design, clear data-governance policy, and funds for making the product economically accessible to small and medium businesses.

Keywords: musculoskeletal disorders; wearable sensors; exoskeletons; occupational ergonomics; technology adoption; implementation barriers; scoping review

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1. Introduction

The number of cases of musculoskeletal disorders (MSDs) have continued to increase, despite age-standardised incidence rates stabilizing or declining, due to population growth and ageing of workforces the largest single contributor to years lived with disability globally [4,5]. According to modelling estimates by the Global Burden of Disease, in 2021, musculoskeletal conditions affected approximately 1.7 billion people and low back pain is the leading cause of years lived with disability in almost all regions around the world [4,6]. In the European Union, 60% of workers are estimated to experience musculoskeletal complaints and musculoskeletal injuries are responsible for a disproportionately large and high percentage of fatal and non-fatal serious occupational accidents [7]. In addition to the physical impact, including pain and functional limitations, work-related musculoskeletal disorders (WMSDs) result in significant direct and indirect economic costs due to the costs of health care use, compensation claims, absenteeism, presenteeism, and the impact on productivity, and estimates of these costs vary by country, but are in the tens of billion dollars per year in some countries (e.g., Canada, United States) [24,38].

Traditional ergonomic risk assessment has been highly dependent on the use of checklists and self-report questionnaires. The methods are low cost and simple to apply, but they suffer from highly subjective raters, low temporal resolution, and lack the ability to record the cumulative loading that is actually responsible for tissue damage, which occurs moment to moment [8,10,12]. It has become technically possible to monitor the biomechanics of a person's body continuously, objectively and in the field, powered by the convergence of miniaturised inertial measurement units (IMUs), surface electromyography (sEMG), flexible pressure sensors and low power wireless connectivity often referred to as Industry 4.0 and more recently as the human-centred Industry 5.0 paradigm at a cost point that is plausible for regular occupational health practice [9,10,15,19]. Meanwhile, occupational exoskeletons have progressed from prototype to commercial products directly available to construction, logistics, manufacturing, and healthcare employers with the help of simple passive spring- or elastic-band-based back- and shoulder-support devices, and others being actively powered [24,26,28,36,38,42,43].

A large and growing number of systematic and scoping reviews have already synthesized evidence on the biomechanical effectiveness of these two technology families: from wearable sensors, high accuracy for identifying risky postures, and lifting tasks, and their potential for real-time feedback and post-hoc ergonomic redesign [9-14,17,20,21]; from occupational exoskeletons, their ability to meaningfully reduce perceived exertion and muscular activation in the assisted joint, especially for overhead and stooped posture lifting tasks [24,26,36,38,42,43]. However, despite the findings that efficacy has been demonstrated in the laboratory and in small-scale, short-term field deployments, there is also a recurring theme in the literature that efficacy in the laboratory and in short-term field deployments has not yet been achieved in the long-term, organisation-wide implementation of these technologies [28,36,45,47,55,60]. This is typically known as the ‘valley of implementation' which is the difference between technological readiness and organisational readiness for ongoing use [39,56].

The current state of the art on implementation barriers is largely specific to either wearable sensors [22,23,25,27,29,30,34] or to exoskeletons [37,44,46,48–50,53,54,58,59] and is fragmented by sector (construction [41,44–46,49,50,55], healthcare [17,36], agriculture [33,52], mining [53], warehousing [54]) and by disciplinary lens (human factors or occupational medicine or management science). To our knowledge, no published review has taken a systematic approach to mapping the literature on implementation barriers across both technology family’s side by side so that common and differing barriers are visible to researchers, employers, ergonomists, and policymakers at the same time. This scoping review was undertaken to fill that gap.

1.1 Review objective and questions

This scoping review aimed to identify, describe, and summarise the nature, extent and range of the published evidence regarding barriers (and associated facilitators) to implementation of wearable sensors and exoskeletons for work-related musculoskeletal disorder prevention in practice. The review was conducted based on the following three research questions:

- RQ1. What are the technical, economic, human-factors, organizational, and regulatory hurdles that have been reported in the implementation of wearable sensors in MSD prevention?
- RQ2. Which biomechanical, psychosocial, economic, organisation and regulatory barriers have been mentioned so far with regards to occupational exoskeleton implementation in MSD prevention?
- RQ3. What are the obstacles and opportunities common to all technology families, and what are the obstacles and opportunities unique to each family, and what do these mean for implementation strategy and future research?

2. Materials and Methods

This review followed the Joanna Briggs Institute (JBI) methodological framework proposed by Arksey and O'Malley, and further developed by Peters et al. [1-3] for the JBI, and Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR). The decision not to conduct a systematic review with meta-analysis was made because the goal was to map the overall extent and nature of a very diverse, cross-disciplinary literature including engineering validation studies, cross-sectional survey studies, qualitative interview studies, Delphi panels and narrative commentary rather than to combine a homogeneous effect size from similar trials.

2.1 Eligibility criteria (PCC framework)

Element	Criterion
Population	Workers and occupational-safety stakeholders (employees, supervisors, ergonomists, safety managers, device implementers) across any industry sector performing manual material handling, repetitive, or sustained-posture tasks.
Concept	Barriers, facilitators, adoption, acceptance, and implementation processes relating to wearable biomechanical/physiological sensors (IMU, sEMG, pressure, or multimodal 'smart workwear') and/or passive or

Element	Criterion
	active exoskeletons used for primary, secondary, or tertiary prevention of musculoskeletal disorders.
Context	Real-world or simulated occupational settings (construction, manufacturing, healthcare, agriculture, mining, warehousing/logistics, and other physically demanding sectors), published in the peer-reviewed or credible grey literature in English.

Sources were selected if they provided empirical data, systematic or scoping synthesis, or substantive expert/practitioner commentary on factors influencing the implementation, adoption, acceptance or use of the target technologies. Sources that did not contain any content related to implementation, such as sources on device engineering, biomechanical efficacy, or clinical rehabilitation exoskeletons, were not included, and neither were sources that were only about consumer fitness wearables that were not in an occupational setting.

2.2 Information sources and search strategy

The methodological approach used (a structured rapid scoping search using tools, as opposed to a multi-database boolean systematic search by an information specialist) is mentioned here explicitly because this review was not a Boolean multi-database systematic search. The terms wearable sensor, inertial measurement unit, electromyography, smart workwear, exoskeleton, exosuit, musculoskeletal disorder, WMSD, ergonomic, occupational, adoption, acceptance, implementation, barrier, and facilitator were combined in the searches and were run in an iterative fashion on a number of major scholarly indexing and full-text aggregation platforms such as PubMed/PMC, ScienceDirect, MDPI journals, SAGE Journals, Taylor & Francis Online, Frontiers, Springer Link, IEEE/arXiv preprint servers, and full-text aggregation on ResearchGate. Between the technologies (wearable sensors) and (exoskeletons) there were ten iterative search rounds to the technologies (implementation barriers, cross-cutting), and disease-burden context, and methodological grounding (PRISMA-ScR).

135 results were found in the first search. Once removed, records that were duplicate indexations of the same underlying article on different platforms (e.g., PubMed abstract, and its full text hosted on ResearchGate) were considered, resulting in the identification of 74 unique sources. A total of 52 sources were retained for title/abstract screening according to eligibility criteria above, charted and are included in the evidence base synthesised in Section 3 and provided in the reference list. Screening and charting were done by a single reviewer with AI-assisted search and extraction processes; following the instructions for scoping reviews [1,3] no formal risk-of-bias or methodological quality appraisal was performed, as the aim was not to estimate the effects, but to map the evidence. The selection process is summarised in Figure 1.

Figure 1. PRISMA-ScR flow diagram of the search and selection process

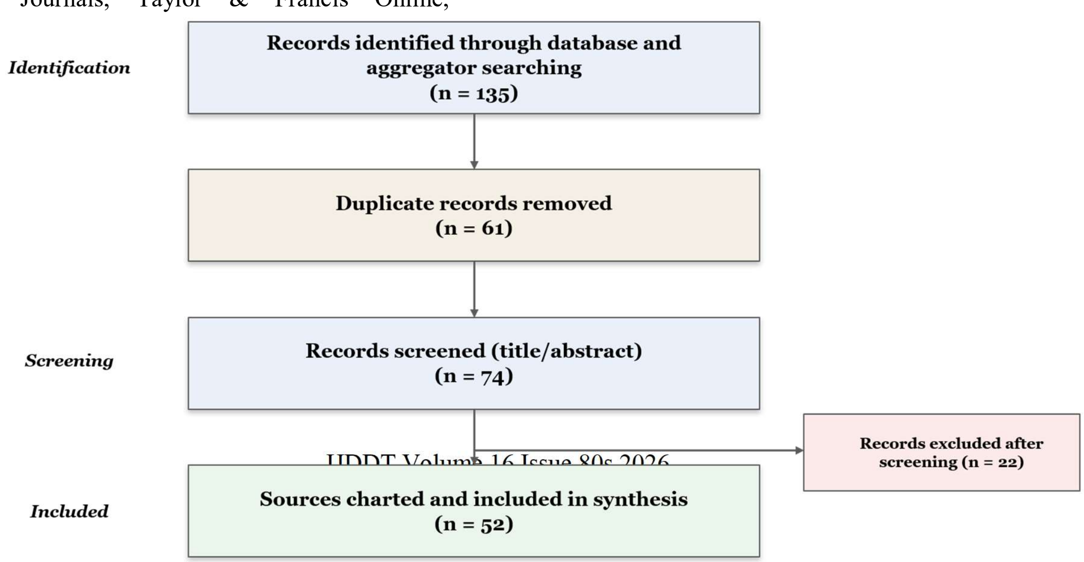
2.3 Data charting and synthesis.

The following information was taken from each source included: technology type (wearable sensor modality or exoskeleton type/actuation), occupational sector, study design, sample and setting, and identified barriers and/or facilitators. Extracted barriers were then inductively organized into thematic domains separately for wearable sensors and exoskeletons, based on the recurring categorizations found in the primary literature (e.g., physiological, work-related, implementation-related, policy and psycho-social barriers) [41,58] and cross tabulated to identify common themes across the two groups. The approach used was narrative synthesis, which was recommended by the descriptive-analytical framing adopted for scoping reviews [1–3].

3. Results

3.1 Overview of the evidence base

Of the 52 charted sources, about two-



thirds focused on the subject of exoskeletons, while one-third focused on wearable sensors, and a small number of sources that were not cross-cutting supported both threads, such as references on disease-burden, privacy-ethics, and methodological. Construction was the most well represented sector, with the physical nature of the work as well as research funding for this sector being particularly high in the North American and European regions [41,44–51,55–57,59]. A smaller, but expanding number of sector-specific studies were represented by the industries of healthcare [17,36], agriculture [33,52], mining [53] and warehousing/logistics [54] also showed rapid growth, with several appearing in the past two to three years, and a diversity of applications that diverges from the construction industry's origins. Study designs ranged from cross-sectional surveys of occupational-safety professionals and workers [23,26,54], through qualitative interview and focus-group studies [44,48,57,58], Delphi panels [44], AHP-based stakeholder ranking studies [45,49], to systematic and scoping reviews synthesising primary evidence [10–14,17,20–22,36–39].

3.2 Barriers to wearable sensor implementation

A set of 5 overlapping barrier domains was seen in the wearable-sensor literature.

Technical and environmental reliability. The ambient conditions of construction and forestry sites including dust, moisture, vibration and extreme temperatures can reduce sensor accuracy, and battery life, wireless connectivity, and durability of repeated donning/doffing are still practical limitations on field deployment [9,22]. One of the main issues reported for low-accuracy IMU- and sEMG-based systems in unconstrained conditions in the field is motion-artefact and calibration drift [10,12,21].

The cost and return of investment. Upfront investment in the hardware, software for integration and training, and costs of ongoing maintenance and training can be a real barrier for SMEs, as the ROI from the wearables is often difficult to quantify and measure, especially if the benefits in terms of injury reduction occur over time and are compounded by the presence of other concurrent safety initiatives [22,23,63].

Data Governance, Data Privacy, Data Trust. This constitutes the most well documented of the barrier domain in the literature. There is a longstanding concern both in the workplace and amongst occupational-safety professionals regarding who owns the collected biomechanical and physiological data, what might be done with it, and whether it is seen as forms of 'big brother' or covert surveillance' [22,23,26,27,29,32,33,34]. It is also pointed out in legal commentary that compulsory programmes of “wearables” – if these are considered as intruding or if they are introduced in an inequitable manner – can lead to discrimination and/or privacy claims against the employer [31]. Proposed mitigations are federated and on-device learning architectures which reduce the amount of raw data transmitted, explicit data-ownership agreements, and the rollout of the solution, led by early adopter champions [9,30,70].

Personal comfort, usability and intrusiveness. Physical comfort, ease of use, and how much a device feels like it is interrupting the normal task performance are strong predictors to sustaining the use of a device, especially in the healthcare environment, where infection control, glove compatibility, and quick turning between patients restrict the placement of a device [17,25].

Immature organization and regulations. Other organisational challenges identified are good-manufacturing-practice-type quality assurance systems, compliance monitoring by employees, and incorporation of the results of the wearables into the current OHS management systems, with no harmonisation of international standards for occupational biomechanical wearables [22,23,30].

3.3 Barriers to exoskeleton implementation

A set of parallel, but different, barrier domains defined exoskeleton literature.

Biomechanical discomfort and anthropometric fit. Pressure points, limited motion, thermal burden under PPE, and poor fit due to the large variation in body sizes found in real working populations, especially smaller workers and women, is the most commonly-observed barrier to exoskeletons [36,37,44,53,55]. Secondary issues of concern include catch-and-snag risk, device weight, and interference with fine motor tasks, which are common concerns [44,49,50].

Task/Environmental compatibility. In laboratory environments, exoskeletons have been shown to be effective for static and repetitive tasks conducted in a single plane, but they may be removed or not used in the construction and mining environments where workers need them most when they are required to perform a variety of tasks quickly, work in confined spaces, climb, and move dynamically [37,38,47,48,53].

Resistance related to psychosocial and identity issues. Factors such as perceived competence signalling ('needing help' perceived as weakness); professional-identity concerns of tradespeople and clinicians; social norms in the crew/ward; supervisor and peer attitudes; and general resistance to visible change all influence the willingness of tradespeople and clinicians to adopt exoskeletons without any objective biomechanical benefit [37,44,52,58,59]. Seasonal or piece work employment and language barriers between migrant workers and device trainers add to the psychosocial resistance and are explored in case studies of non-adoption in agriculture [52].

Uncertain return on investment, cost and financing. Costs of device acquisition, personal device fitting and training are significant, and in markets like the USA and some parts of western Europe where there are no government subsidy schemes to incentivize investing the benefits from the injury-reduction are uncertain and slow to accrue for the employer, especially in construction where there are many small contractors and sub-contract workers [45,49,56].

Human resources readiness and capability. The lack of staff who are trained to select, fit, maintain, and evaluate exoskeletons is a recurring structural barrier, and the lack of standardised selection frameworks, matching the device type, the workers, and the tasks [44,54,56] compounds this. Most thorough assessment of technology readiness-levels is still limited to laboratory or short simulated-task environments, and very few devices tested in both the laboratory and the entire spectrum towards routine use [39].

Immature regulatory and standards. The definition of exoskeletons as PPE, tools or, in certain configurations, medical devices is inconsistent across jurisdictions, as is the guidance on risk assessment and safe implementation [41].

3.4 Cross-cutting themes and facilitators

Table 2 presents a cross-family comparison of barrier domains that have been identified in similar form in the two technology families, plus the most commonly cited facilitators in the charted literature.

Cross-cutting theme	Wearable sensors	Exoskeletons	Facilitators reported
Comfort/usability	Device placement, donning/doffing burden [17,25]	Fit, weight, thermal load, snag risk [36,44,53]	User-centred/participatory design; iterative field fitting sessions [37,44,48]
Cost/ROI	Hardware, integration, maintenance [22,23]	Acquisition, fitting, training [45,49,56]	Pilot programmes; phased financing; government subsidy models [56]
Trust/social acceptance	Data ownership, surveillance concerns [22,26,27,32,34]	Stigma, identity, peer/supervisor norms [37,52,58,59]	Voluntary opt-in; early-adopter champions; transparent communication [30,70]
Task/context fit	Accuracy degraded in harsh field conditions [9,10,21]	Poor fit for dynamic/varied or confined-space tasks [37,47,48,53]	Task-specific device selection frameworks [38,54,56]
Organisational readiness	Lack of integration into OHS systems [22,23,30]	Lack of trained fitters/evaluators; unclear TRL [39,44]	Leadership buy-in; dedicated implementation champions [46,48]
Regulatory maturity	Absent international standards [22,30]	Inconsistent device classification [41]	Emerging guideline and standards development efforts [41,56]

In this cross tabulation two integrative observations arise. First, with wearable-sensor barriers, it's not so much the barrier itself that is problematic as much as what happens to the data the device produces; with exoskeleton barriers, it's not so much the barrier itself that's problematic, as much as what the barrier does to, and how it visibly signals about, the person wearing it. Second, while the emphasis is different, both literatures share the same list of practical facilitators: involvement of workers in the device selection and fitting process from early on and throughout, strong and consistent leadership support, the device being offered to the group voluntarily, rather than through mandates, and the device being evaluated in the field over a longer period of time than has been observed so far in most trials [37,44,46,48,60].

3.5 Sector- and worker-level considerations

Several sources on the charted list point out that there are not equal implementation challenges across the workforce. In the field of exoskeletons, attitudinal factors such as perceived usefulness and social perception were the most significant predictors of adoption intention, whereas perceived obstacles were less significant, and there were only small differences in exoskeleton readiness by sex and age (though there were larger differences by body size and sex, which were reported as a perceived obstacle) [54] (see also Section 2.1 for attitudinal barriers discussed by a survey of the exoskeleton literature). The same issues of weight and confined space compatibility arose in Mining-sector exploratory research [53]. Based on typology, they identify a number of categories of non-users, such as those who actively reject the device or those who stopped using it after a brief period of trial, or those who are effectively excluded and don't use it because of poor fit of the device, which has implications for tailoring the approach to implementation instead of using a single universal approach [59].

4. Discussion

This scoping review charted a patchwork quilt of evidence documenting the reasons why wearable sensors and exoskeletons, both of which have been clearly shown to reduce biomechanical exposure that can lead to musculoskeletal injury, are not yet widely used in everyday work. These findings confirm and build on previous sector-specific reviews, in which the two technology families (sensors and exoskeletons) were often grouped together under the 'wearable technology for MSD prevention' label, but are actually exposed to significantly different primary barriers: data governance and trust for sensors, and embodied physical and psychosocial acceptance for exoskeletons.

4.1 An implementation-science lens

The barrier domains identified here align well with the multi-level determinants more prevalent in implementation-science frameworks used in clinical settings, and include innovation characteristics, worker (individual) characteristics, inner organisational context, outer policy/regulatory context, and the implementation process. When viewed from this perspective, 'comfort' and 'fit' are barriers to innovation, ‘stigma' and ‘trust' are barriers at the individual and social-context level, ‘lack of trained fitters' and ‘absence of integration into OHS systems' are barriers at the inner-setting level and ‘financing' and ‘regulatory classification' are barriers at the outer-context level [39,41,44,56]. Few of the charted studies were explicitly based on such an implementation framework; most of the studies were rather created inductively from surveys or interviews. In order to compare and aggregate the barriers identified in future primary research in a more systematic manner across studies and across sectors, there needs to be explicit adoption of implementation-science frameworks in future primary research.

4.2 The persistence of the efficacy–implementation gap

A common theme across the literature charted is that while there is a wealth of laboratory and short-term field-based efficacy studies, there is a lack of organisation-scale implementation studies involving adoption, long-term use, and discontinuation over several years [28,36,39,60]. The technology-readiness-level analyses demonstrate that the overwhelming majority of the evidence is at simulated-task or short-duration level of field-trials, and truly operational, multi-year deployments are still few [39]. This is a trend that has long been known from digital-health implementation research overall, in which efficacy studies frequently outnumber real-world adoption studies. It will likely take review journals and funding bodies to put as much emphasis on rigorous implementation and de-implementation studies as on device-validation studies to close this gap.

4.3 Equity, inclusiveness and workforce diversity

Anthropometric mismatch, meaning devices designed and sized around a smaller range of body types than the workforce, was also a barrier for wearable sensors (comfort, sensor placement) and exoskeletons (fit, range of motion, and effectiveness) [36,44,53,54]. Insufficient consideration of inclusive sizing can risk perpetuating occupational health inequities, as women and smaller statured workers are more likely to be under-served by devices sized for the average or male anthropometric profile. Few charted studies explicitly discussed adoption or fit by gender or body size, indicating a need for more deliberate research design in the future.

4.4. Scale up financing and organisation.

Small and medium sized businesses and businesses that heavily depend on subcontracting or seasonal workers often experience greater cost barriers, as the entity most affected by the cost of the injury may not be the one responsible for acquiring the product [45,49,52,56]. Larger adoption conditions were reported to occur when government subsidy or cost-sharing schemes were used, compared to the U.S. system, which is mostly employer self-funded [56]. This indicates that financing-model design is not a side effect of implementing technologies, but it is a part of the structure of the technology's ability to reach the smaller employers and more precarious workforce that arguably have the highest MSD risk.

4.5 Practical implications

The charted evidence suggests a consistent implementation playbook for employers and safety practitioners, including: engaging workers as early as possible during design or selection; conducting pilot phases first with voluntary early adopters; clearly define what data is collected, who accesses it, and why it is being collected; factor in time to fit, train and maintain, as these are recurring costs; and plan for field evaluation periods to be long enough to see beyond novelty effects to real behaviour change. The evidence base suggests a broader anthropometric design envelope, the modular task-specific configuration, and a less monolithic data-processing architecture on-device or federated, to decrease the framing of the surveillance model that always undermines trust [9,32,70]. Harmonizing of device classification and means of financing devices that would be more easily available to smaller employers is more likely to reduce the efficacy-implementation gap, for policy makers and standards bodies, than be incremental improvements in sensor accuracy or exoskeleton torque output.

5. Limitations

- Not a formally performed Boolean search by an information specialist on PubMed, Scopus, Web of Science and Embase, but a structured, tool-based rapid search done on scholarly aggregators; some potentially relevant articles indexed only in databases other than those in this search footprint may not have been found.
- The screening and charting were done by one reviewer, which does not satisfy the dual-independent-reviewer standard recommended for highest-rigour scoping reviews and as a result, an interrater reliability statistic is not reported.
- The search was limited to English-language sources, and may have missed relevant implementation evidence from other-language publications, especially from research groups in East Asian, and continental European, languages.
- As is typical in a scoping review, the methodological quality or risk of bias of each of the specific studies reviewed was not formally assessed and the review does not report on the strength or certainty of evidence supporting each individual claim, but rather describes the range and pattern of reported barriers.
- The number of construction-sector studies in the charted evidence base was larger than the numbers for the other sectors, and this could underestimate implementation barriers in these other sectors, such as healthcare, agriculture, and mining sectors, that may be distinct and more severe.

6. Conclusion

Wearable sensors and work exoskeletons both have real and supported potential to decrease biomechanical exposures that cause work-related musculoskeletal disorders. However, this scoping review reveals that a recurrent and non-technical group of barriers has been identified, that hinder the translation of the validated technologies into routinely used occupational practice, these being data trust and governance for sensors; physical fit, task compatibility and psychosocial acceptance for exoskeletons; and, for both technologies, unresolved financing, organisational readiness and regulatory standardisation. To achieve meaningful scale-up of the efficacy implementation gap, occupational-health research needs to commit to the same level of focus and investment in longitudinal, worker-centred implementation science as has already been done for device-level biomechanical validation, and design practices and funding models must be created to achieve the same scale of workplace adoption as they have for the musculoskeletal risk, which is often highest in smaller, more precarious workplaces.

Declarations

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Conflict of Interest: The authors declare no conflict of interest.

Author Contributions: Conceptualisation, methodology, writing, review and editing.

Data Availability: All data charted for this scoping review are derived from the publicly available published sources cited in the reference list.

Ethical Approval: Not applicable; this article is a scoping review of previously published literature and did not involve human or animal subjects.

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