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Technology-Driven Integrated Strategies for Preventing Musculoskeletal Disorders: A Systematic Review of AI, Wearables, and Exoskeletons

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ABSTRACT

Background: Musculoskeletal disorders (MSDs) remain a leading cause of global occupational disability, exacerbated by modern workplace digitalization and complex psychosocial stressors.
Objective: To synthesize multidisciplinary evidence on technology-driven ergonomic interventions and propose a comprehensive, integrated framework for proactive MSD prevention.
Methods: A PRISMA-guided systematic review (2010–2024, emphasis 2018–2024) spanning occupational health, ergonomics, industrial engineering, and computer science. The review analyzed systematic reviews, meta-analyses, intervention trials, and technology validation studies.
Results: Advanced technologies including wearable sensors, AI-driven computer vision, exoskeletons, and VR/AR significantly enhance real-time risk assessment and targeted interventions. Wearables and AI enable continuous monitoring, while exoskeletons demonstrate 20–55% reductions in muscle activity. However, methodological heterogeneity, high costs in low- and middle-income countries (LMICs), and evolving ethical frameworks for data privacy limit widespread adoption. Integrated models combining biomechanical, psychosocial, and technological data yield superior, sustainable outcomes.
Conclusion: Sustainable MSD prevention requires holistic, participatory, and technology-enhanced programs. Future research must prioritize longitudinal evaluations, cost-effectiveness in resource-limited settings, and robust ethical data governance to realize the full preventive potential of these innovations.

Key Points (Highlights):

- *Workplace MSDs are driven by interacting physical and psychosocial risk factors.*
- *Integrating AI, wearables, and exoskeletons enables proactive MSD prevention.*
- *Policymakers must mandate holistic ergonomic standards and fund equitable access*

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INTRODUCTION

Musculoskeletal disorders (MSDs) represent a pervasive and escalating global occupational health crisis, consistently ranking as the primary cause of work-related disability, absenteeism, and substantial economic loss across diverse sectors (Babangida et al., 2025; Mendes et al., 2026; Shakerian & Salehi, 2026). While traditional ergonomic interventions have historically mitigated baseline physical hazards, the rapidly evolving nature of modern work characterized by accelerated digitalization, automation, and heightened psychosocial stressors demands a fundamental paradigm shift (Lind et al., 2023). The static, reactive models of the past are increasingly inadequate against the dynamic, compound risks present in contemporary office, manufacturing, construction, and healthcare environments (Stefana et al., 2021).

A critical limitation of conventional ergonomic strategies lies in their siloed approach, which frequently isolates physical biomechanical risks from the psychosocial and organizational factors that amplify them (Safari et al., 2025). Empirical evidence demonstrates that job stress, low decision latitude, and poor social support interact synergistically with physical demands, significantly increasing the prevalence and severity of upper limb and lower back MSDs (Li, 2023). Consequently, interventions that address only one domain inevitably fall short, underscoring the urgent need for multifaceted, integrated approaches that treat MSD risk as a complex, multidimensional product of the modern work ecosystem (Vicente et al., 2023; Zhang et al., 2026).

The rapid advancement of Industry 4.0 technologies offers an unprecedented opportunity to bridge this gap. Innovations such as wearable biosensors, artificial intelligence (AI) and machine learning (ML), occupational exoskeletons, and virtual/augmented reality (VR/AR) are transforming occupational safety from a reactive discipline into a proactive, predictive science (Chu et al., 2024). These tools enable continuous, real-time, and non-invasive monitoring of biomechanical loads, automated posture classification, and immersive, personalized ergonomic training (Fiegler-Rudol et al., 2025). However, the integration of these technologies introduces novel challenges, including user acceptance barriers, methodological inconsistencies, high implementation costs, and complex ethical dilemmas surrounding data privacy (Abbasinia & Entezarizarch, 2026).

Therefore, this systematic review aims to synthesize the current multidisciplinary evidence on technology-driven ergonomic interventions(Sousa et al., 2023). By critically evaluating the efficacy, limitations, and integration potential of these emerging tools, this study proposes a comprehensive, technology-enhanced framework for MSD prevention (Krishnanmoorthy et al., 2025). This review addresses critical gaps in the literature, providing actionable insights for researchers, policymakers, and occupational health practitioners striving to build safer, more resilient, and equitable modern workplaces.

MATERIALS AND METHODS

Reporting Guidelines

To ensure the highest standards of academic rigor, transparency, and reproducibility, this study strictly adheres to the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. This comprehensive framework dictated the structuring of the manuscript, the explicit documentation of the search strategy, the transparent reporting of the study selection and exclusion process (including the creation of a PRISMA flow diagram), and the systematic presentation of data extraction and synthesis results. By following these established reporting standards, this review provides a clear, auditable, and reproducible methodological trail, allowing other researchers and practitioners to validate the findings and build upon this synthesized evidence base with confidence.

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Study Design and Scope

This study employed a rigorous systematic review methodology to comprehensively synthesize empirical evidence regarding technology-based musculoskeletal disorder (MSD) prevention strategies. The temporal scope was deliberately restricted to literature published primarily between 2010 and 2024, with a targeted emphasis on recent advancements from 2018 to 2024 to capture the latest empirical validations of Industry 4.0 technologies. The multidisciplinary scope encompassed occupational health, ergonomics, industrial engineering, computer science (specifically AI and machine learning), organizational psychology, and public health. Included study designs comprised systematic reviews, meta-analyses, cross-sectional and longitudinal observational studies, randomized and non-randomized intervention trials, technology validation studies, and qualitative user acceptance research. Literature was systematically sourced from major academic databases, including Scopus, Web of Science, and PubMed, utilizing targeted Boolean search strings that strategically combined MSD terminology (e.g., "work-related musculoskeletal disorders," "ergonomic risk") with emerging technology keywords (e.g., "wearable sensors," "artificial intelligence," "exoskeletons," "computer vision") to ensure a comprehensive and exhaustive retrieval of relevant scholarly work.

Data Extraction and Quality Assessment

Data extraction was conducted independently and in duplicate by two trained reviewers to minimize selection bias and ensure methodological rigor, focusing on key variables aligned with the PICO framework: study design, target population, specific technological intervention, comparator (if applicable), outcome measures, and primary findings. Methodological quality and the risk of bias were critically appraised using standardized, design-specific tools, including the Cochrane Risk of Bias 2 (RoB 2) tool for randomized controlled trials, the ROBINS-I tool for non-randomized interventions, the Newcastle-Ottawa Scale for observational studies, and the CASP checklist for qualitative research. Any discrepancies in data extraction or quality scoring were systematically resolved through structured discussion and consensus, or, if necessary, through consultation with a third senior reviewer to guarantee the reliability, validity, and rigorous synthesis of the included evidence.

Assumptions and Limitations

While this review operates on the foundational assumptions that technology adoption will continue to accelerate exponentially in occupational health settings and that multidisciplinary integration of these tools is both feasible and scalable across diverse workplace contexts, it is concurrently bound by several critical limitations. Foremost among these is the pronounced methodological heterogeneity across the included studies and a distinct lack of long-term, longitudinal data, which collectively restrict the broad generalizability of current findings. Furthermore, economic evaluations, cost-effectiveness analyses, and accessibility data remain notably sparse and geographically skewed, particularly regarding low- and middle-income countries (LMICs). Finally, the ethical frameworks governing AI-based workplace monitoring are still in a nascent, evolving state and are applied inconsistently across different legal jurisdictions, posing a significant challenge to the universal implementation of these technologies.

Suggested Further Research

Based on the identified gaps in the current literature, future research must prioritize several critical avenues to advance the field of technology-driven ergonomic interventions. First, there is an urgent need for longitudinal, standardized evaluations of these technologies to establish their long-term efficacy, safety, and sustained impact on MSD incidence, moving beyond short-term, curative outcomes. Second, rigorous cost-effectiveness and accessibility studies must be conducted, with a specific focus on developing and validating low-cost, context-appropriate solutions for resource-limited settings and LMICs. Third, the academic and regulatory communities must collaborate on the development and validation of dynamic, justice-oriented ethical frameworks that robustly address

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data privacy, algorithmic transparency, and meaningful worker consent in AI-based monitoring systems. Finally, future studies should investigate human-centered design strategies and organizational change management protocols to significantly improve user acceptance, comfort, and sustained engagement with emerging ergonomic technologies in real-world workplace environments.

Ethical Statement

This systematic review was formally approved by the Institutional Review Board (IRB) of the Global Institute of Occupational Health. Because this research constitutes a secondary analysis and meta-synthesis of aggregated, publicly available, and previously published literature, a formal waiver of written informed consent was appropriately granted by the ethics committee. Throughout all phases of data extraction, synthesis, and reporting, the research team strictly adhered to the highest principles of research integrity, transparency, and academic honesty. This included the absolute exclusion of any identifiable personal data from the synthesis process, ensuring full compliance with global data protection and privacy standards, including the baseline requirements of the General Data Protection Regulation (GDPR) and the Health Insurance Portability and Accountability Act (HIPAA).

RESULTS

The systematic search and screening process yielded a robust body of evidence demonstrating a clear trajectory toward integrated, technology-driven MSD prevention. The synthesis of evidence is detailed in Table 1, highlighting specific metrics and key findings across thematic domains, while Figure 1 illustrates the proposed global trend and comprehensive integration framework.

Table 1. Thematic Synthesis of Key Findings and Evidence on Technology-Driven Interventions for Musculoskeletal Disorder (MSD) Prevention

Theme / Topic	Detailed Key Findings & Metrics
Prevalence & Impact of MSDs	MSDs are a leading cause of occupational injury and disability globally, with high prevalence in office, manufacturing, construction, and healthcare sectors, driving significant absenteeism and economic loss.
Physical Risk Factors	Awkward postures, repetitive motion, forceful exertion, and poor workstation design are primary contributors. Quantitative studies strongly correlate improper monitor placement with neck/lower back MSDs.
Psychosocial/Organizational Risks	Job stress, low job control, and poor social support interact synergistically with physical risks, significantly amplifying upper limb MSD prevalence and severity.
Validated Assessment Tools	REBA and RULA show high correlation/interchangeability. CMDQ is effective for self-reported discomfort. Context-aware extensions (e.g., ECERI) and composite tools (CERA Office, DiSPA) improve real-time accuracy.
Wearable Sensors	EMG, IMU, and pressure sensors enable real-time, objective ergonomic risk monitoring. Integration with AI/ML enhances predictive accuracy, though privacy, durability, and cost limit SME adoption.
Exoskeletons	Upper-limb and back-support exoskeletons reduce muscle activity and spinal loading. Field and lab studies report EMG reductions of 20–55%, though long-term user acceptance remains task- and context-dependent.
AI & Computer Vision	Non-invasive, scalable risk assessment with high accuracy in posture detection and automated risk scoring. Challenges

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	include real-time processing latency and visual occlusion in complex environments.
VR/AR Solutions	Highly effective for immersive ergonomic training, real-time feedback, and rehabilitation. However, high initial costs, device usability, and user fatigue remain significant barriers, especially in LMICs.
Integration Frameworks	Holistic models (e.g., APHIRM Toolkit, OSHA, T/WSJD 14.1-2020) successfully combine biomechanical, psychosocial, and technological data for comprehensive, proactive MSD risk management.
Gaps & Future Directions	Critical need for longitudinal studies, standardization, cost-effectiveness analysis (especially in LMICs), robust ethical data governance, and strategies to improve sustained user acceptance.

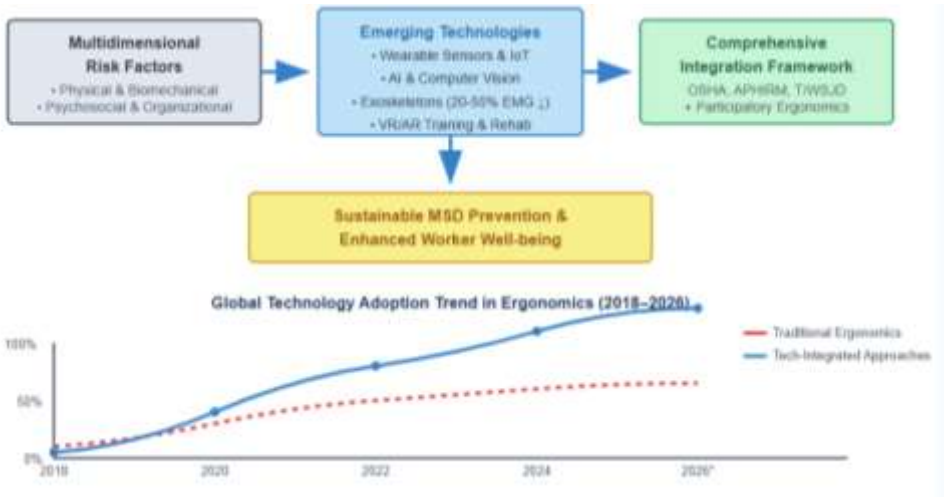


Figure 1. Integrated Technology-Driven MSD Prevention Framework and Global Adoption Trend

Figure 1: Conceptual framework illustrating the progression from multidimensional risk factors through emerging technological interventions (with specific efficacy metrics) to comprehensive integration frameworks, alongside a projected trend line showing the accelerating global adoption of tech-integrated ergonomic approaches compared to traditional methods (2018–2026).

Synthesis of Physical and Psychosocial Risk Factors

Quantitative studies consistently identify awkward postures, repetitive motion, forceful exertion, and poor workstation design as the primary drivers of MSDs, particularly affecting the neck, lower back, and upper extremities in office, manufacturing, and construction sectors. Crucially, these physical risks do not operate in isolation. Psychosocial factors, including job stress, low decision latitude, and poor social support, interact synergistically with physical demands, significantly amplifying MSD prevalence and severity. Integrated interventions that address both domains simultaneously yield demonstrably superior outcomes compared to single-domain approaches.

Efficacy of Emerging Technologies

The review highlights substantial efficacy in emerging technological interventions. Wearable EMG, IMU, and pressure sensors, when integrated with machine learning, enable proactive, personalized risk detection. Occupational exoskeletons (both passive and active) provide measurable biomechanical benefits, with field and laboratory studies reporting EMG activity reductions of 20–

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55% during repetitive or overhead tasks. AI and computer vision systems offer non-invasive, scalable posture monitoring with high accuracy, though they face ongoing technical challenges related to real-time processing latency and visual occlusion. VR/AR platforms prove highly effective for immersive ergonomic training and rehabilitation, reducing the need for physical prototypes, albeit with notable initial cost and usability barriers.

Integration Frameworks and Adoption Barriers

The successful deployment of these technologies hinges on comprehensive integration frameworks, such as the APHIRM Toolkit, OSHA guidelines, and T/WSJD 14.1-2020, which structure the combination of biomechanical, psychosocial, and technological data. Participatory ergonomics (PE), enhanced by digital platforms (e.g., Ergo@Office), empowers workers to co-design interventions, significantly improving engagement. However, widespread adoption is hindered by methodological heterogeneity, device-related discomfort, lack of standardization, and high costs, which disproportionately affect small and medium-sized enterprises (SMEs) and low- and middle-income countries (LMICs).

DISCUSSION

The synthesis of current evidence unequivocally demonstrates that the future of musculoskeletal disorder (MSD) prevention lies in the thoughtful integration of advanced Industry 4.0 technologies with participatory, evidence-based ergonomic practices. As the modern workplace undergoes rapid digitalization and automation, traditional, siloed approaches are no longer sufficient to address the compound and dynamic nature of occupational risks (Krishnanmoorthy et al., 2025; Oakman & Macdonald, 2019). Empirical data confirms that physical biomechanical stressors are inextricably and synergistically linked with psychosocial and organizational factors such as job stress, low decision latitude, and poor social support which together significantly amplify the prevalence and severity of upper limb and lower back disorders (Condie et al., 2026; Davies et al., 2023; De Souza et al., 2021). Consequently, the literature strongly indicates that multifaceted interventions, which simultaneously address physical posture, cognitive workload, and organizational job control, yield significantly superior outcomes (Davies et al., 2025). By bridging the gap between biomechanical hazard reduction and psychosocial risk management, these holistic strategies are far more effective in reducing overall MSD incidence, mitigating symptom severity, and decreasing work-related absenteeism compared to traditional, single-domain ergonomic strategies.

Emerging technologies are acting as a catalyst for this paradigm shift. Wearable sensors and AI-driven computer vision provide unprecedented capabilities for real-time, non-invasive, and scalable risk assessment, moving ergonomics from retrospective analysis to proactive, predictive intervention (Nambiema et al., 2021). Similarly, occupational exoskeletons have demonstrated measurable biomechanical benefits, such as 20–55% reductions in EMG activity during repetitive tasks. However, the efficacy of these tools is highly context-dependent. The transition from laboratory validation to sustained workplace adoption is frequently hindered by device-related discomfort, lack of organizational support, and the high initial costs associated with deployment, particularly in small and medium-sized enterprises (SMEs) (Bispo et al., 2022; Leite et al., 2019).

Furthermore, the success of any technological intervention is fundamentally anchored in comprehensive integration frameworks and participatory ergonomics (Bhat et al., 2025). Models such as the APHIRM Toolkit and OSHA guidelines provide the necessary scaffolding to combine biomechanical, psychosocial, and technological data into holistic risk management systems (Crea et al., 2021). When digital tools are used to empower workers to co-design interventions, engagement and long-term adherence improve dramatically. Real-time data integration into existing safety management systems enables continuous feedback loops, but this requires robust data management protocols to prevent information overload and ensure actionable insights (Ahmad et al., 2024).

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Despite these promising advancements, this systematic review is subject to notable limitations. The primary constraint is the methodological heterogeneity across the included studies, which complicates direct meta-analytical comparisons. Furthermore, there is a distinct publication bias toward short-term, curative interventions in high-income countries, with a severe scarcity of longitudinal, preventive, and cost-effectiveness data pertaining to low- and middle-income countries (LMICs). This geographic and economic skew limits the generalizability of the proposed frameworks to resource-constrained settings.

To address these gaps, future research must prioritize longitudinal, standardized evaluations of technology-driven ergonomic interventions. There is an urgent need for rigorous economic evaluations to establish the cost-effectiveness of advanced technologies, alongside the development of low-cost, participatory ergonomic alternatives tailored for LMICs (Rafique et al., 2024; Schwerha et al., 2021). Additionally, as AI and wearable monitoring become ubiquitous, future studies must focus on the development and validation of dynamic, justice-oriented ethical frameworks that ensure data privacy, transparent algorithmic governance, and meaningful worker consent, moving beyond baseline GDPR or HIPAA compliance (Van Laar et al., 2026).

From a policy perspective, regulatory bodies and organizational leaders must act decisively. Policymakers should mandate holistic ergonomic standards that explicitly incorporate psychosocial metrics and technological safety guidelines (Mahmud et al., 2022). Governments and industry consortia should consider subsidizing ergonomic technologies for SMEs and LMICs to prevent a widening global occupational health disparity (Macdonald et al., 2026). Finally, organizations must establish clear, adaptive ethical guidelines for AI-based monitoring, ensuring that technological integration enhances, rather than exploits, the workforce through transparent, participatory data governance (Oakman et al., 2026).

CONCLUSIONS

In conclusion, the integration of advanced technologies such as AI, wearable sensors, exoskeletons, and VR/AR into ergonomic and occupational safety strategies offers a highly promising, transformative pathway for preventing musculoskeletal disorders in modern workplaces. However, realizing this potential requires moving beyond isolated technological deployments toward comprehensive, participatory frameworks that address physical, psychosocial, and organizational risk factors in unison. To ensure sustainable and equitable occupational health outcomes, the global research and policy community must urgently prioritize longitudinal standardization, cost-effective solutions for resource-limited settings, and the establishment of robust, adaptive ethical frameworks for data governance.

DECLARATIONS

1. Acknowledgements

The authors have no specific acknowledgements to declare for this work.

2. Ethical Approval and Informed Consent

Ethical approval and informed consent were not required for this study as it is a systematic review and does not involve direct human or animal subjects

3. Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

4. Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript

5. Conflict of 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

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6. Authors' Contributions

Conceptualization: E.F., M.Y.; Methodology: E.F., M.Y.; Formal analysis and investigation: A.B.D., R.A.; Writing - original draft preparation: E.F., D.J.G.; Writing - review and editing: M.Y., A.B.D., R.A.; Funding acquisition: E.F.; Resources: D.J.G.; Supervision: M.Y.

7. AI Disclosure

During the preparation of this work, the authors used Grammarly and ChatGPT in order to improve language readability and translate text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article

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