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Integration of AI-Based Ergonomics in Early-Stage Building Design: A Frame Work for Enhancing Occupational Health in Construction Projects

Author: Arlovia Acevedo Noboa
Civil Engineer – Occupational Health and Safety Specialist
Troya Railway Constructions
EURING (Engineers Europe)
ASSP (American Society of Safety Professionals)
WORK FORCE SAFETY HUB
Madrid, Spain

ORCID

(Arlovia Acevedo Noboa[1])

Abstract

This article presents a novel framework for incorporating artificial intelligence (AI) algorithms, specifically machine learning and computer vision, during the early design stages of architectural and engineering processes, aimed at predicting ergonomic risks in construction projects. [1] [7] [13].

Unlike existing approaches that consider ergonomics only during the construction or operational phases, this proposal moves prevention forward to the design stage, when spatial and functional decisions already have a direct impact on occupational health [4] [8] [9].

The system merges digital modeling with data mining tools applied to posture analysis, physical loads, and areas of potential ergonomic risk, integrating these into Building Information Modeling (BIM) platforms commonly used in construction [1] [7] [13]. The strategy also aims to prevent work-related accidents, injuries, and fatalities, thereby improving productivity and reducing costs in civil construction [11] [12].

It is flexible in its alignment with various international standards and scalable at a global level [6] [10]. This research contributes to a broader and more proactive vision of engineering design, in line with the principles of human and technological sustainability promoted by the Journal of Engineering, Design and Technology.

Keywords

Artificial Intelligence, Ergonomics, Early-Stage Design, Occupational Health, Construction Safety, Predictive Modeling

The construction sector remains one of the industries with the highest risks to occupational health [12] [11]. In particular, work-related musculoskeletal disorders (MSDs) are a leading cause of absenteeism, reduced productivity, and increased medical costs. Despite advancements in technology and safety regulations, ergonomic risks are still addressed reactively typically late in the construction process or only once issues have already arisen on site.

Meanwhile, artificial intelligence (AI) is being increasingly adopted across engineering and design disciplines. Software applications in the industry commonly support structural analysis, energy optimization, and project management. However, their use as tools to predict ergonomic risks during the early design phase where spatial, geometric, and functional decisions can still be modified remains in its infancy or is nearly nonexistent [7].

This paper introduces a novel methodology that integrates AI technologies with ergonomic principles to identify and prevent postural and biomechanical risks at the earliest stages of architectural and engineering design. This not only facilitates safer working environments but also supports productivity and long-term sustainability in the construction sector.

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The primary objective is to establish a methodological framework for incorporating AI algorithms (e.g., machine learning and computer vision) within digital modeling environments (e.g., BIM) to enable early prediction of potentially hazardous ergonomic conditions before construction begins. Such approaches promote a preventive, scalable, and globally adaptable solution in compliance with standards such as ISO 11226 [6], OSHA [10], and national occupational health guide-lines.

1. INTRODUCTION

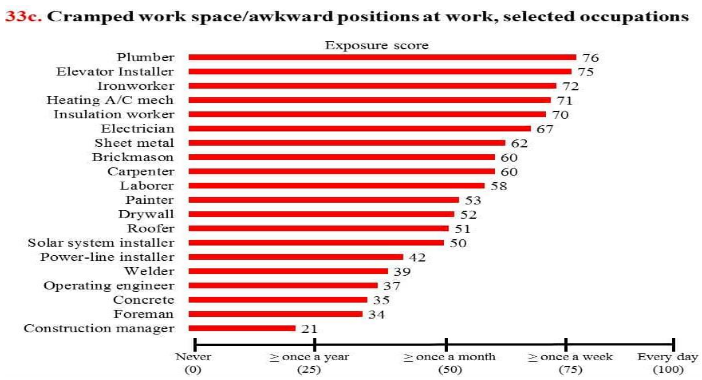

Figure 1. Prevalence of Musculoskeletal Disorders (MSDs) in the Construction Industry. Rate of MSDs in the construction sector compared to other industries. Source: Project Safety Journal.

2. THEORETICAL FRAMEWORK

2.1. Ergonomics in Construction: Ongoing Challenges

Ergonomics in the construction industry focuses on adapting working conditions to the capabilities and limitations of the human body. Numerous studies have reported a high prevalence of work-related musculoskeletal disorders (MSDs) among construction workers, particularly during tasks involving repetitive loads, awkward postures, or manual material handling [11] [12].

Evaluation methods such as REBA (Rapid Entire Body Assessment), RULA (Rapid Upper Limb Assessment), and the NIOSH Lifting Equation are widely used to assess ergonomic risks [4] [8] [9]. However, these tools are predominantly applied manually and reactively often after workers are already on-site and operating under fixed conditions.

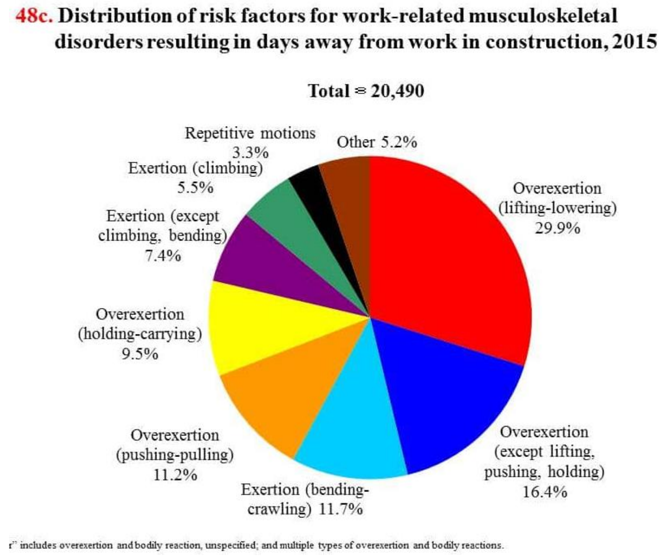

Figure 2. Distribution of risk factors for work-related musculoskeletal disorders (WMSDs) causing work absence in the construction sector (2015). Overexertion during lifting/lowering.

2.2. Artificial Intelligence in Architectural and Engineering Design

In the fields of architecture and engineering, artificial intelligence (AI) has gained attention for its applications in automatic floor plan generation, energy-conscious design, structural analysis, and sensor data interpretation [2] [3] [13].

Machine learning techniques, neural networks, and evolutionary algorithms have demonstrated their capacity to recognize complex patterns and propose adaptive design solutions. Nevertheless, the use of AI to predict ergonomic risk factors before a physical workspace has been constructed remains an emerging and largely unexplored area. While some preliminary studies have explored computer vision or biomechanical modeling to assess posture risks, these approaches remain fragmented and rarely integrated into mainstream design workflows [1] [7] [13].

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Figure 3. Overview of work-related musculoskeletal disorders (WMSDs), their main symptoms, affected body parts, contributing factors, and prevention strategies. Source: European Agency for Safety and Health at Work (EU-OSHA), 2020.

2.3. Digital Modeling and Human-Centered Design

With the rise of Building Information Modeling (BIM) and other 3D modeling systems, new opportunities have emerged to integrate ergonomics and occupational health considerations into the digital design workflow [1] [7] [13].

Human-centered design places emphasis not only on how a building looks or performs but also on how it affects the health, safety, and efficiency of the people who build or use it. This multidisciplinary approach enables the correlation of geometric, spatial, and functional parameters with biometric and biomechanical data, establishing a more holistic perspective on risk prevention [5] [11].

2.4. Limitations of Current Approaches and Integration Opportunities

Although some initiatives exist to digitize ergonomic assessments, there is a lack of systematic strategies for applying AI algorithms to forecast risks during the design phase. This gap represents a major opportunity to develop predictive tools capable of simulating tasks, analyzing posture, and utilizing anthropometric data to recommend ergonomic improvements and reduce risk exposure [1] [4] [9].

The technical and financial feasibility of such an approach is supported by current digital modeling technologies, and its implementation could significantly enhance compliance with international occupational safety regulations [6] [10].

3. METHODOLOGY

Building upon the theoretical insights presented in the previous section, this paper proposes a four-phase methodology for integrating artificial intelligence (AI) algorithms into ergonomic evaluation during the architectural and engineering design stages. The focus is on digital modeling environments particularly BIM where construction tasks, postures, and workflows can be simulated. In this way, ergonomic risks can be detected and mitigated before implementation on the construction site [1] [7] [13].

The project is initially developed using a three-dimensional model with BIM tools such as Autodesk Revit or ArchiCAD [13]. In addition to architectural and structural components, the model includes access zones, working heights, material handling areas, and construction sequences. This framework supports the creation of spatially realistic contexts for simulating actual construction scenarios [1] [7].

3.1. Phase 1: Digital Modeling of the Work Environment

The project is initially developed using a three-dimensional model with BIM tools such as Autodesk Revit or ArchiCAD. In addition to architectural and structural components, the model includes access zones, working heights, material handling areas, and construction sequences. This framework supports the creation of spatially realistic contexts for simulating actual construction scenarios [1] [3].

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3.2. Phase 2: Capture and Generation of Ergonomic Data

AI models are fed with data from multiple sources, including:

- International anthropometric databases (e.g., ISO - 7250 or regional datasets) [5] [6].
- Posture simulations using tools like Jack (Siemens) or the AnyBody Modeling System.
- Virtual environments where human avatars perform simulated construction tasks.

The study focuses on tasks such as lifting, collecting, carrying, and working at heights [4] [8] [9].

3.3. Phase 3: Development and Implementation of AI Algorithms

Supervised machine learning classifiers (e.g., random forests or neural networks) are trained with datasets labeled according to ergonomic risk levels based on REBA, RULA, or NIOSH criteria. These datasets include synthetic data generated through digital human modeling tools (e.g., Jack, AnyBody), complemented by publicly available anthropometric databases such as ISO 7250 and regional sources [5] [6]. These algorithms are trained to predict risk associated with individual design configurations such as element heights, material locations, or circulation paths.

In addition, computer vision techniques are integrated to assess joint angles, forced postures, and estimated exposure times. The outputs are visualized as heatmaps overlaid on the BIM model, highlighting ergonomic risk zones [1] [13].

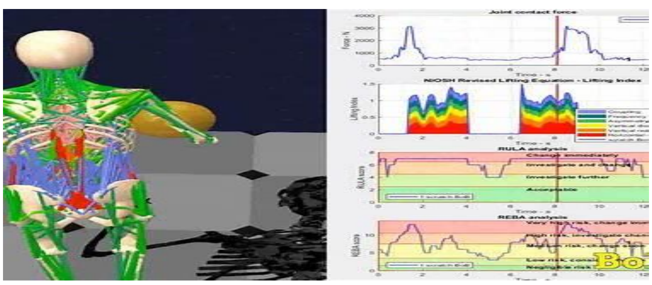

Figure 4. Example of integrated ergonomic risk evaluation using biome-chanical simulation. Joint contact forces, NIOSH lifting index, RULA, and REBA analyses are shown for a lifting task, supporting real-time risk pre-diction in digital human modeling environments.

3.4. Phase 4: Validation and Feedback into the Design

The algorithm outputs provide actionable feedback for the design team, including automatic recommendations such as modifying heights, adjusting assembly sequences, or redesigning access routes [1] [13]. Initial validation involves comparing the AI-predicted results with expert human ergonomic assessments to evaluate accuracy, sensitivity, and practical relevance [4] [8].

This methodology aims to promote preventive decision-making during design, treating occupational health as a design variable as critical as functionality or energy efficiency right from the project's inception [7].

4. APPLICATION IN THE CONSTRUCTION SECTOR

The proposed method represents not only a technical innovation but also a practical response to the urgent needs of the construction industry, which demands early identification of ergonomic risks and proactive mitigation to ensure safe and productive working conditions [1] [11] [12].

Below are three key domains where AI-assisted ergonomic design can significantly enhance construction practices. For instance, in a simulated analysis of a hospital construction site, the proposed AI system identified excessive upper limb elevation during overhead HVAC installations. Based on this output, the design team modified ceiling access points and work heights, reducing predicted REBA scores from high to moderate risk levels [1] [4] [8] .

4.1. Risk Assessment Requirements and Exposure Control

This anticipatory approach makes it possible to document compliance with international standards such as ISO 11228, OSHA 1926, and local equivalents [6] [10]. AI-based predictive modules can serve as supplementary risk analysis tools, automatically identifying high-risk zones and suggesting corrective actions directly within digital design plans [1] [13].

4.2. Maintenance and Decommissioning Procedures

By incorporating ergonomic simulations early in the design process, safer and more accessible procedures can be pre-planned [1] [7]. This is especially valuable in industrial projects, hospitals, or large-scale infrastructure, where ongoing maintenance is intensive and critical.

4.3. Training and Personal Protective Equipment (PPE)

Early identification of ergonomic hazards also supports more accurate workforce training and better planning of personal protective equipment (PPE) needs. This allows training programs to be tailored to actual ergonomic risks rather than generic scenarios [5] [9].

5. DISCUSSION

The anticipated outcomes of the proposed framework suggest that the use of artificial intelligence (AI) during architectural design processes can predict potentially hazardous ergonomic conditions with greater precision than conventional post-hoc analysis methods [1] [4] [8] [13].

This predictive capacity, enabled through collaborative digital modeling platforms such as BIM, facilitates early intervention, allowing spatial and functional decisions to be corrected before they materialize as harmful environments [7] [13].

The comparison between AI-generated predictions and traditional ergonomic tools (e.g., REBA, NIOSH) indicates AI's potential to complement or outperform manual evaluations [4] [8] [9].

While standards such as ISO and OSHA provide valuable guidelines, they were not designed for digital design workflows [6] [10]. This methodology helps push regulations toward a more proactive and integrated model.

Further, dynamic, data-driven practices should be adopted using predictive analytics and integrating ergonomics as a core design variable from the start [1] [7].

However, limitations include data scarcity, variability across countries, and regulatory fragmentation [11] [12]. Ethical considerations such as algorithmic accountability and human oversight are also essential.

6.1. Study Limitations

Despite the promising outcomes of this framework, several limitations must be acknowledged. First, the absence of empirical testing in real-world construction sites means that the algorithmic predictions have yet to be validated under dynamic field conditions. Second, the quality and representativeness of the training data are constrained by the availability of ergonomic datasets, which may not fully capture regional variations, gender differences, or specific trade activities.

Additionally, regulatory differences across countries may affect the scalability and standardization of the approach. These limitations highlight the need for further testing, broader data integration, and collaborative efforts to adapt the methodology to diverse construction contexts.

6. CONCLUSIONS AND FUTURE WORK

This framework shows that bringing artificial intelligence into the early design stages of construction projects can shift the way we approach workplace safety. Instead of reacting to risks once workers are already exposed, this method helps identify and reduce ergonomic hazards from the very beginning when decisions about space, materials, and workflows are still flexible [1] [13].

By simulating real-world tasks and environments, this approach enables data-driven design decisions that not only help prevent musculoskeletal disorders (MSDs) but also enhance productivity and ensure regulatory compliance [4] [6] [10].

Looking ahead, there are several areas that deserve deeper exploration:

- Testing the system in real-life construction projects.
- Expanding ergonomic datasets to reflect different popular

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tions and work types.

- Creating BIM plug-ins for real-time feedback during design.
- Aligning the tool with international regulations

and ensuring that ethical concerns like transparency and human oversight are built into every stage [1] [5] [7] [11].

In conclusion, this research offers not only a technological innovation but a paradigm shift toward human-centered, prevention-oriented design in the construction sector.

More than just a technical solution, this research contributes to a design culture that puts people first. It points toward a future where technology doesn't just build structures but also protects the health, dignity, and well-being of those who build them. Ultimately, integrating human-centered design and artificial intelligence at the earliest stages of development represents a transformative shift toward safer, smarter, and more sustainable construction environments.

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