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APPLICATION OF ERGONOMICS IN AI-INTEGRATED SMART MANUFACTURING SYSTEMS

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Abstract

Artificial Intelligence (AI) is revolutionizing modern manufacturing systems through automation, predictive analytics, and human–machine collaboration. While AI enhances efficiency, the integration of ergonomics ensures that worker health, safety, and performance are not compromised. This article explores the application of ergonomics in AI-integrated smart manufacturing systems, emphasizing human–AI interaction, cognitive workload, musculoskeletal disorder (MSD) prevention, and the role of real-time monitoring tools. It examines ergonomic design frameworks, wearable technologies, and adaptive AI-driven interventions to optimize both safety and productivity. The discussion highlights developments up to 2021, outlining how ergonomics and AI converge to create sustainable, human-centered smart factories.

Keywords: Application of ergonomics, Artificial intelligence (ai), Smart manufacturing, Human–machine interaction, Industry 4.0, Workplace safety, Automation and robotics, Occupational health, Human- centered design, Productivity optimization, Digital twins, Predictive maintenance, Cognitive ergonomics, Cyber-physical systems, Human factors engineering, Workplace efficiency, Intelligent automation, Collaborative robotics (cobots), Safety management systems, Sustainable manufacturing.

Introduction

The fourth industrial revolution, widely referred to as Industry 4.0, has ushered in a new era in manufacturing, characterized by the integration of artificial intelligence (AI), robotics, machine learning, cyber-physical systems, and the Internet of Things (IoT). Smart factories powered by these technologies are capable of self-optimization, predictive maintenance, and autonomous decision-making, enabling organizations to enhance productivity and remain globally competitive (Lee, Kao, & Yang, 2014; Ghobakhloo, 2018). By 2021, numerous industries— including automotive, electronics, and pharmaceuticals—had begun adopting AI-enabled solutions to streamline production, reduce downtime, and increase flexibility in responding to consumer demand. While technological progress has redefined efficiency, it has also introduced new ergonomic challenges. Increased reliance on intelligent systems has shifted the human role from direct manual labor to supervisory and cognitive tasks, raising concerns about mental fatigue, cognitive overload, and postural stress in human–robot interaction. (Carayon, 2021; Jarrahi, 2018). Ergonomics, therefore, plays a pivotal role in ensuring that workers remain central to the design and operation of AI-integrated systems. Without such consideration, there is a risk that advances in automation may undermine human health, reduce job satisfaction, and lead to costly workplace injuries.

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The convergence of AI and ergonomics offers unique opportunities to build human-centered smart factories. AI-powered monitoring systems can detect fatigue, wearable technologies can track postural deviations, and digital twins can simulate human–machine interactions before implementation. These tools not only prevent injuries but also optimize workflow design and improve job satisfaction. By 2021, ergonomic applications in AI-based environments were gaining attention from both academia and industry as a way to balance efficiency with worker well-being. This article investigates the role of ergonomics in AI- integrated manufacturing systems, focusing on the design, application, and future prospects of human- centered approaches within Industry 4.0.

Ergonomic Considerations in AI-Integrated Systems: Smart manufacturing environments require careful consideration of both physical and cognitive ergonomics. As human workers collaborate with AI-enabled robots, interact with augmented reality (AR) and virtual reality (VR) interfaces, and oversee increasingly complex automated processes, new ergonomic risks emerge. *Physical ergonomics* is particularly important in manufacturing tasks such as lifting, carrying, assembly, and repetitive motions. AI-integrated systems can analyze postural data in real time, identifying unsafe bending or twisting that may contribute to musculoskeletal disorders (MSDs). For example, computer vision systems equipped with deep learning algorithms can automatically assess worker movements and provide corrective feedback (Zhang & Chen, 2021). Wearable devices such as smart exoskeletons or posture monitors have also become more common, enabling early detection of fatigue and promoting safer movement patterns.

Cognitive ergonomics presents equally critical challenges. In AI-driven environments, workers are often required to make high-stakes decisions quickly while monitoring vast amounts of information. The use of augmented reality glasses and advanced HMIs (human–machine interfaces) can enhance situational awareness, but they also increase the risk of cognitive overload if not ergonomically designed. Research has shown that improper task design in human–AI interactions may lead to errors, stress, and lower performance. Thus, ergonomics ensures that information is presented clearly, workloads are balanced, and user interfaces are intuitive. Another major consideration is organizational ergonomics, which addresses how work is structured, how responsibilities are allocated between humans and AI systems, and how team collaboration is managed. As AI takes over repetitive tasks, workers are often reallocated to oversight and troubleshooting roles, which require training and adaptation. The success of AI–human collaboration depends not only on technical integration but also on organizational structures that support ergonomic well-being. By 2021, it was evident that ergonomic considerations must be embedded into every stage of AI system design— ranging from equipment development to workplace layout and task allocation. Without such integration, smart factories risk creating environments that undermine human health and performance, despite gains in efficiency. In integrating ergonomics into AI-driven workplaces ensures that technology supports rather than overwhelms workers. Properly designed systems reduce cognitive overload, improve decision-making, and promote worker well-being, making human–AI collaboration safer and more effective.

Applications of Ergonomics in AI Systems: One of the most significant applications of ergonomics in AI- powered manufacturing is the use of digital twins. Digital twins are virtual models that simulate real- world operations, allowing designers to test human– machine interactions before actual deployment. By modeling how workers interact with machines, organizations can identify potential ergonomic hazards and redesign workflows proactively (Lee et al., 2014). *Predictive analytics* represents another major application. AI systems can analyze movement data collected from sensors and detect early signs of ergonomic risks. For example, repetitive motion data may indicate increased risk of carpal tunnel syndrome or back strain. By predicting these risks, organizations can intervene before injuries occur. AI-powered collaborative robots are increasingly used to reduce physical strain in repetitive or heavy-lifting tasks. Robots can be programmed with ergonomic algorithms to adjust lifting speed, force, and posture support, reducing the physical burden on workers. In assembly lines, robots can assist with high-precision tasks while ensuring that workers are not exposed to hazardous condition.

Wearable technologies such as smart gloves, exoskeletons, and posture-tracking vests have also emerged as powerful AI-integrated ergonomic tools in modern workplaces. These devices continuously collect biomechanical data such as joint angles, muscle load, heart rate, and posture deviations, which are then analyzed by AI algorithms to provide real-time feedback and corrective recommendations. For instance, posture-tracking vests can alert workers when they maintain unsafe bending positions, while exoskeletons reduce lumbar compression forces during lifting tasks by redistributing load away from vulnerable spinal regions. Smart gloves equipped with haptic sensors can monitor repetitive hand movements and grip strength, helping identify early signs of upper-limb disorders. Importantly, the data generated from these wearable systems can be aggregated at the organizational level to guide redesign of workstations, modify task allocation, and develop personalized ergonomic interventions. Thus, AI-enhanced wearables transform ergonomics from a reactive approach, traditionally focused on treating injuries, into a proactive, data-driven system for preventing work-related musculoskeletal disorders.

In addition to wearables, AI-enabled ergonomic monitoring systems are increasingly being embedded into workplace infrastructure. Smart cameras and computer-vision systems can automatically track worker movements, detect unsafe postures, and classify task-related ergonomic risks in real time. These systems eliminate the need for manual observation, which is often subjective and labor-intensive. Machine-learning algorithms can continuously refine risk detection accuracy by learning from large datasets of human movements across different industrial settings. As a result, organizations can conduct continuous ergonomic surveillance, generate automated risk reports, and implement targeted interventions such as workstation redesign, rotation scheduling, or additional training for high-risk workers.

Another emerging application is the integration of ergonomics into intelligent work scheduling and task allocation systems. AI can evaluate individual worker fatigue levels, biometric indicators, past injury records, and task difficulty to recommend optimal rest breaks and assign jobs that minimize cumulative ergonomic load. This prevents overexertion and distributes physically demanding tasks more evenly across workers. In highly automated environments, AI systems can also dynamically reconfigure workflows in response to detected ergonomic risks—such as redirecting heavy lifting tasks to robotic systems or modifying assembly-line speed when fatigue indicators rise. This convergence of AI and ergonomics supports the transition toward human-centered smart manufacturing, where productivity gains are achieved without compromising worker health and well-being.

A further development in AI-driven ergonomics is the personalization of ergonomic solutions based on individual worker characteristics. Traditional ergonomic guidelines are often generalized, assuming uniform physical capabilities across workers. However, AI systems can account for variations in age, gender, anthropometry, fitness level, and prior injury history. By learning from individualized biomechanical data, AI can recommend customized workstation heights, tool designs, and lifting limits tailored to each worker. This individualized approach significantly enhances ergonomic effectiveness, especially in diverse workforces such as manufacturing, logistics, and healthcare, where physical demands and worker capabilities vary widely. Personalized ergonomics not only improves safety but also enhances comfort and productivity by reducing physical and cognitive strain.

AI is also transforming ergonomic training and education through virtual reality (VR) and augmented reality (AR) platforms. These immersive technologies allow workers to practice safe movement techniques and correct postures in simulated environments before performing real tasks. AI-powered training systems can assess a worker's performance during simulations, identify risky movements, and provide real-time corrective guidance. For example, AR headsets can overlay visual cues onto a worker's field of view, showing optimal lifting angles or safe reach distances during task execution. Such interactive training increases retention of ergonomic principles and supports continuous learning, moving beyond traditional one-time safety workshops to ongoing, adaptive skill development.

Finally, AI-based ergonomics enables continuous improvement in workplaces by analyzing data from sensors and wearables to detect risk patterns. These insights help redesign tools, adjust workflows, and prevent injuries, ensuring that technological progress support worker safety and comfort.

Benefits of Ergonomics in Smart Manufacturing: Integrating ergonomics into AI-based manufacturing environments provides multifaceted benefits for both workers and organizations. On the individual level, ergonomic interventions reduce the risk of workplace injuries and musculoskeletal disorders, which are among the leading causes of absenteeism in manufacturing industries. By addressing both physical and cognitive stressors, AI-driven ergonomic systems help maintain worker health and promote long-term employability.

From an organizational perspective, ergonomic systems enhance productivity and efficiency. Workers who are physically comfortable and mentally engaged are less prone to errors and can sustain performance for longer durations. Furthermore, ergonomic strategies reduce turnover rates and improve employee morale, as workers perceive their well-being as a corporate priority.

Financially, the integration of ergonomics in AI-based systems leads to cost savings by minimizing injury- related compensation claims and reducing downtime associated with worker fatigue. Studies have shown that ergonomic improvements can deliver a significant return on investment, especially in industries where labor costs and health expenditures are substantial. Perhaps the most strategic benefit lies in creating sustainable and human-centered smart factories. By 2021, it was widely recognized that technological advancement alone could not ensure competitiveness; worker well-being had to be prioritized to achieve sustainable industrial growth. Ergonomics provides the foundation for aligning AI-driven efficiency with human safety, thereby creating environments where technology and people complement rather than replace each other.

Beyond immediate operational gains, the integration of ergonomics in smart manufacturing also strengthens organizational resilience and innovation capacity. Healthy workers are more capable of adapting to new technologies, participating in continuous improvement programs, and engaging in problem-solving activities on the shop floor. AI-supported ergonomic systems encourage participatory design, where worker feedback is incorporated into equipment layout and task design, fostering a culture of safety and collaboration. This human-centered approach not only reduces long-term health risks but also supports knowledge retention, as experienced workers are more likely to remain in their roles rather than exit due to injury or fatigue.

Organizational and Social Dimensions: AI adoption changes work structures, requiring organizational ergonomics to clarify roles and balance responsibilities. Workers often shift from machine operators to data interpreters, making training and upskilling essential. Social concerns also arise, including job displacement fears and reduced autonomy. Addressing these requires transparent communication, participatory decision-making, and the assurance of meaningful human roles. Trust in AI is equally important. Designing robots with intuitive communication and fostering collaboration between humans and machines can enhance acceptance. In essence, organizational and social ergonomics help AI adoption strengthen workplace culture instead of disrupting it.

Challenges and Limitations: Several barriers complicate ergonomic integration in AI-driven systems. Technologically, AI depends on accurate workplace data, which may be incomplete or biased. Wearables, though useful, can be intrusive and reduce worker compliance. High implementation costs also limit adoption, especially for SMEs. Ethical concerns around privacy and surveillance arise when monitoring biometric and cognitive data. Moreover, the absence of standardized ergonomic guidelines for AI workplaces and resistance to change among workers further constrain progress.

Future advancements: Future advancements may enable personalized ergonomic systems using exoskeletons, multimodal data, and human digital twins for predictive interventions, while inclusive training, regulations, and collaboration among ergonomists, AI developers, and policymakers will ensure human-centered, smart factories.

Conclusion: By 2021, AI applications such as robots, wearables, and digital twins were already reshaping manufacturing ergonomics. These technologies reduce risks but introduce challenges related to costs, ethics, and worker acceptance. A balanced approach that integrates physical, cognitive, and social ergonomics ensures smart factories remain safe and sustainable. Rather than replacing humans, AI should augment human performance, creating workplaces that combine innovation with well-being.

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