Smart Wearable Devices for Work Efficiency Optimization and Human-Machine Collaboration

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Abstract. This review explores the latest advancements in industrial wearable technology for work efficiency and promoting human-machine collaboration. The article outlines the primary types of wearable devices formed by their unique sensor components and functions. It discusses how these devices improve ergonomics and enhance task performance through three key functionalities. The report further explores the role of wearable devices as interfaces in human-machine teams, where data sharing and adaptive responses enable better coordination between workers and automated equipment. Finally, the report identifies the main challenges limiting the broader adoption of industrial wearable devices and highlights prospects. As industries continue to undergo digital transformation, understanding the capabilities and impacts of smart wearable devices is crucial for leveraging them to create safer, more efficient, and more collaborative workplaces.

Keywords: Wearable Technology; Industrial Ergonomics; Human-Machine Collaboration; Work Efficiency; Industry 4.0.

1. Introduction

In the era of Industry 4.0, manufacturing systems are becoming increasingly complex, requiring seamless coordination between humans and intelligent machines. Traditional ergonomic tools and management methods often fail to keep pace with these rapid changes. Smart wearable devices with real-time sensing and feedback capabilities are emerging as a crucial bridge between human workers and digital systems. These devices can continuously collect objective data about human physical conditions, behavior, and the working environment, providing a data-driven foundation for process optimization and safety enhancement.

Recent studies have demonstrated their effectiveness in various sectors. However, limitations remain: most applications are confined to laboratory or pilot-scale environments, and challenges such as data privacy, user comfort, and system integration hinder large-scale adoption. Moreover, existing reviews often focus only on specific sensor types or isolated use cases, lacking a holistic view of how wearable technology integrates into broader human–machine systems.

Therefore, this review aims to provide a comprehensive overview of industrial wearable devices for improving work efficiency and human-machine collaboration. It categorizes device types by sensor functionality, evaluates how wearables improve safety and productivity, and explores their role in collaborative decision-making and system feedback. This research offers timely insights into how wearable technology can enable smarter and more resilient industrial systems.

2. Types and Functionalities of Wearable Devices

Smart wearable devices typically comprise multiple sensor components capable of continuously sensing human physiological and environmental parameters to enable data-driven real-time feedback [1, 2]. Depending on the monitoring target, wearable sensors can be broadly categorized into three groups: biomechanical sensors, physiological sensors, and environmental and task sensors (e.g., vibration or pressure sensors) [3]. Fusing these diverse sensing modules allows wearable devices to monitor workers' status during operations comprehensively [4]. Table 1 summarises the main sensor types and their measurement indicators.

Wearable devices typically realize their functions by embedding such sensors into wearable form factors. Studies show that multi-sensor integrated “sensor systems” are among the most employed solutions in ergonomics research [1, 2]. For example, a full-body sensor suit may include multiple IMUs distributed across the head, torso, and limbs to collect real-time kinematic data of the whole body[5]. This can be complemented by surface EMG electrodes capturing muscle exertion and in-shoe pressure pads measuring foot load distribution, thereby assessing working postures and forces in combination [6]. Compared to traditional observational methods, these objective quantitative measures accurately represent workers' risk exposure and support targeted ergonomic interventions [2]. It is noteworthy, however, that complex multi-sensor systems often require careful calibration and fitting, and thus may not be immediately ready-to-wear without proper setup [7].

Table 1. Major wearable sensors and their monitored variables in industrial applications.

Sensor Type	Key Measured Variables	Typical Use Cases
IMU (Inertial Measurement Unit)	3-axis acceleration, angular velocity, orientation	Posture monitoring, motion tracking, fatigue assessment
Surface EMG sensor (sEMG)	Muscle electrical signal amplitude, fatigue indices	Muscle effort monitoring, fatigue warning
Foot Pressure sensor	Plantar pressure distribution, center-of-gravity shift	Postural stability, gait analysis, fatigue detection
Heart Rate/Physiological sensor	Heart rate, heart rate variability, galvanic skin response	Cardiopulmonary load monitoring, fatigue and stress tracking
Vibration/Environmental sensor	Mechanical vibration exposure, acceleration shocks, ambient conditions	Vibration exposure monitoring, hazardous environment detection

In addition to the sensing modules themselves, various wearable terminal devices serve as platforms to implement these functions. In industrial environments, common wearables include smartwatches or wristbands, smart helmets, smart glasses, smart vests or garments, and smart insoles [5,8]. For example, a smartwatch or wristband embedded with IMUs and an optical heart-rate sensor can monitor arm motions and heart rate, which is useful for tracking work duration and detecting fatigue [5]. Smart helmets or smart glasses equipped with cameras, displays, and sensors can provide an augmented reality interface to workers, overlaying digital instructions during assembly or maintenance tasks [8]. Additionally, smart insoles measure foot pressure and gait patterns, effectively monitoring fatigue and detecting slip or trip hazards in sectors like construction[9]. By aligning device capabilities with use-case needs, wearable technology is increasingly embedded in industrial workflows, becoming a key medium in Industry 4.0 for human-machine interaction[8].

3. Wearables in Work Efficiency Enhancement

Smart wearable devices enhance work efficiency and safety performance through multiple channels. On the one hand, they provide real-time, objective data feedback to help workers promptly correct poor postures and movements, thereby reducing the risk of workplace injuries and improving productivity [1, 4]. On the other hand, the big data collected by wearable sensors can be used to analyze process bottlenecks and worker status, supporting evidence-based process improvements and decision optimizations[5].

3.1 Posture Recognition & Fatigue Monitoring

Wearable sensors enable continuous tracking of workers' posture and fatigue levels. Inertial measurement units (IMUs) are commonly used due to their small size and minimal interference with work tasks. They allow real-time identification of unsafe postures and immediate alerts, significantly improving posture standardization and reducing injury risk [5][10]. Naranjo et al. reported a 38% improvement in ergonomic risk scores after using wearables, compared to traditional monitoring [1].

Besides posture, fatigue detection is another key application. Physiological sensors like heart rate monitors and skin conductance devices can assess fatigue by measuring heart rate variability (HRV) and other bio-signals. This helps detect excessive fatigue and issue warnings to the worker or supervisor. According to Moon and Ju, such real-time, data-driven fatigue assessments enable proactive health management in industrial settings [10]. These sensor-based evaluations correlate strongly with expert assessments, validating their reliability in identifying hidden fatigue risks [6].

By continuously monitoring posture and fatigue, companies can reduce injury rates, lower downtime, and maintain workers' physical and cognitive performance. This prevents productivity losses caused by fatigue-related errors or absenteeism [1][11].

3.2 Real-time Feedback & Task Guidance

Smart wearable devices monitor risk factors and actively guide users through real-time feedback. Many devices integrate haptic vibration alerts, audio/visual signals, and AR displays to provide intuitive and immediate warnings. For instance, waist-worn devices with motion sensors can vibrate when detecting an excessive trunk bending angle, prompting workers to adjust their posture and reduce the risk of lower-back injuries [2]. Ergonomics research has confirmed the effectiveness of such haptic feedback in correcting improper lifting behavior and minimizing musculoskeletal strain [10]. Similarly, smart helmets and wristbands can detect signs of severe fatigue or hazardous environmental conditions, issuing alerts that allow workers to pause or avoid risk, thus enhancing workplace safety and reducing the chance of injury-related downtime [1].

Augmented reality (AR) interfaces further support task navigation by projecting real-time step-by-step guidance, data, and warnings into the worker's field of view. This hands-free delivery of instructions improves accuracy and execution speed, especially in complex industrial settings [8]. In immersive training, virtual reality (VR) simulations offer a safe environment to rehearse dangerous or complicated tasks. Naranjo et al. reported that forklift operators trained using VR experienced approximately 30% less muscle stress than those trained through conventional methods, without compromising learning outcomes [1]. In another case, VR was used to validate virtual workstation layout changes in a manufacturing plant, leading to a 20% reduction in worker fatigue and a 15% productivity increase after implementation [1].

3.3 Data-Driven Process Improvement

Wearable devices continuously collect large volumes of objective data, enabling process optimization at the organizational level. By analyzing multi-dimensional sensor data, managers can uncover inefficiencies and hidden risks not detectable by traditional means and implement targeted improvements [1]. For instance, wearable motion and force data can classify work tasks and associated risks via machine learning [6][12]. Peters et al. found that physically demanding tasks like material handling could be distinguished with over 90% accuracy, despite most results coming from lab environments [12]. This highlights the potential of wearables to quantify worker contributions, enabling more effective personnel allocation and process flow design.

Wearable data also supports a continuous improvement cycle: identifying issues, applying interventions, and validating results through follow-up measurements. For example, a wearable accelerometer field study found cashier movements linked to musculoskeletal risks. Another factory deployed sensor networks to identify high-strain activities; workstation redesigns then reduced worker fatigue and improved line efficiency. According to Naranjo et al., such ergonomic improvements led to fewer injuries and lower absenteeism while increasing productivity and saving costs [1].

In summary, wearable data enables a shift from static assessments to dynamic, evidence-based decision-making. By embedding these insights into workflow design, companies can continuously enhance safety, efficiency, and human-centric practices [8].

4. Integration with Human–Machine Systems

Smart wearable devices serve as the interface and bridge between humans and machines, enhancing the human-machine interaction experience, improving collaborative efficiency, and incorporating human factors data into system decision-making[8].

4.1 AR/VR Enhanced Interfaces

Advancements in augmented and virtual reality have transformed human-machine interfaces. AR smart glasses can project real-time process data, machine status, and peer feedback into the user's field of view, seamlessly integrating digital and physical environments. In complex assembly tasks, AR guidance reduces errors and improves task accuracy and speed by showing the correct installation steps and lowering the cognitive load required for information retrieval. These interfaces enable focused, efficient, and intuitive collaboration. A review in Nature Electronics highlights AR’s convergence with AI and IoT as a significant trend in wearable development, enabling real-time, personalized assistance and enhancing the user experience [8].

VR offers immersive environments for collaboration and simulation, which is especially valuable during training and workstation design. Naranjo et al. reported that forklift operators using VR-based training alongside AGVs experienced ~30% less muscle strain than conventional training, without sacrificing performance [1]. In another case, VR simulations helped automotive engineers test and optimize workstation layouts. Post-implementation, ergonomic fatigue dropped by 20%, and productivity increased by 15% [1]. VR also enables pre-deployment drills, allowing workers and robots to simulate workflows and resolve conflicts without interrupting production.

Overall, AR and VR wearable interfaces improve collaboration by enhancing human understanding of machine tasks while enabling machines to respond to human behavior through sensor data [8]. This two-way feedback lays the foundation for highly coordinated and adaptive human-machine teams.

4.2 Collaboration Efficiency and User Experience

Wearable assistive devices are increasingly important for enhancing human-machine collaboration efficiency. A notable example is the industrial exoskeleton, which provides mechanical support to reduce muscle strain, enhance strength, and improve productivity. Field studies in sectors such as automobile assembly confirm that lower-limb or trunk exoskeletons can significantly reduce work-related injury downtime and boost throughput. These findings illustrate how wearable assistive devices augment human capabilities in high-intensity tasks. However, user experience challenges persist: workers often report limited flexibility, poor fit, or discomfort with prolonged use. Some designs lack adaptability to different body types, indicating the need for ergonomic improvements to ensure comfort and wider acceptance[5].

Beyond mechanical support, wearable technology improves collaboration through real-time data sharing. Robots and autonomous systems can receive live location and motion-intent signals from wearable sensors, dynamically adjusting their behavior for safer and more efficient cooperation. In material handling, posture and location data help robots avoid collisions or synchronize precisely with human actions. In assembly, arm-mounted sensors can indicate a worker's task stage, allowing robots to deliver parts on time and reduce delays. With AI-driven analysis, collaborative systems can autonomously adapt to human habits, creating smoother coordination[8].

Wearable data also enhances the human–machine interaction experience. Stress-monitoring devices, for instance, can inform robot control systems to reduce speed or force, easing worker tension and improving psychological safety. This real-time adaptation increases trust and enables fuller use of automation. Naranjo et al. reported that deploying an AI-based fatigue monitoring system in logistics warehouses reduced workplace injury rates by about 15%, showing how sharing worker data allows proactive system adjustments[1]. Such outcomes demonstrate that wearable integration improves efficiency and builds worker satisfaction and confidence in automation.

In summary, wearable technologies are central to building high-performance human–machine teams. They create safer and more efficient collaboration by reducing physical strain, synchronizing workflows, and enhancing trust. Addressing ergonomic design and acceptance challenges will be critical for their broader adoption and long-term success.

4.3 Human Factors in System Feedback

In smart factories, human condition data are increasingly used to optimize system decisions. Ergonomic indicators such as fatigue, stress, or physiological load, collected via wearable devices, can be fed into scheduling or equipment control, enabling closed-loop feedback between humans and machines. For instance, fatigue monitoring on assembly lines allows algorithms to slow cycle times or insert breaks when abnormal fatigue is detected, reducing accidents and ensuring production stability[10]. Studies show that incorporating worker health status into scheduling reduces fatigue-related errors and improves efficiency. Naranjo et al. reported that after a logistics firm adopted AI-driven fatigue monitoring, workplace accidents fell by about 15%. Similarly, a manufacturer using VR and wearable ergonomic assessments identified poor layouts and saved roughly $200,000 annually in reduced rework[1]. These cases highlight the safety and economic value of integrating human factors into decision-making.

At a collaborative level, data sharing promotes adaptive optimization. Traditionally, machines followed static rules, lacking awareness of human intent. Wearables now allow real-time observation of “soft” information such as fatigue, stress, or concentration, enabling algorithms like multi-agent systems or adaptive control to adjust strategies dynamically. For example, robotic assistants can vary speed or force based on heart rate or slowed movements, while scheduling systems can distribute workloads according to team fatigue[8]. This adaptive capacity ensures systems rebalance in real time, maximizing efficiency while safeguarding health.

Beyond immediate optimization, accumulated human-factor data also informs long-term strategy. Managers can leverage these insights to design more scientific scheduling policies, targeted training, and better interfaces, ultimately strengthening organizational resilience and competitiveness.

Integrating human-centric feedback through wearables shifts industrial collaboration toward a more innovative and resilient paradigm, delivering benefits for safety and efficiency.

5. Challenges and Future Directions

Despite the promise of smart wearables, large-scale adoption in industry faces several barriers. Data security and privacy remain primary concerns: wearable sensors collect extensive personal health and behavior data, and without strong safeguards, risks of leaks or misuse increase[11]. As workplaces become more connected, robust cybersecurity and encryption are essential. High integration costs and a lack of standards also hinder adoption. Advanced IoT sensors, AI algorithms, and AR hardware require significant investment, especially for SMEs. Moreover, the wearable market is fragmented, with incompatible data formats and interfaces raising integration complexity. A recent living review stressed the need for standardized sensor interfaces and evaluation frameworks to ensure system comparability [7].

User experience and ergonomics present further challenges. Bulky or intrusive designs discourage long-term use, and feedback from field studies shows some exoskeletons lack flexibility or proper fit[5]. Future designs must be lighter and adaptable to diverse body types to ensure comfort and acceptance. At the same time, AI integration raises concerns about bias and ethics. Limited or skewed training data may yield inaccurate or unfair outcomes, emphasizing the importance of transparency and fairness checks.

Finally, research gaps remain. Current studies focus mainly on developed nations and manufacturing sectors, while emerging economies and service industries remain underexplored. Given the rapid pace of technological development, academic research often lags. Doherty et al.propose a “living review” approach to continuously update evidence on device accuracy and effectiveness[7].

In summary, progress in data protection, standardization, ergonomics, and fairness is essential to unlock the full value of smart wearables. Through cross-disciplinary cooperation and global knowledge sharing, these devices can help realize a safer, smarter, and more human-centric Industry 4.0[8].

6. Conclusion

This review found that various smart wearable devices, such as sensor-embedded clothing, smart insoles, AR headsets, and powered exoskeletons, can significantly improve work efficiency and support human-machine collaboration. They can monitor workers' posture and fatigue levels in real time, providing objective data to help prevent injuries and reduce occupational strain. They also offer timely feedback and guidance (e.g., through haptic cues or augmented reality overlays) to correct technique, improve task accuracy, and shorten training cycles. In human-robot team environments, wearable devices can interface to share human operators' status and intentions with machines, enabling better coordination and adaptive automated responses. Nevertheless, challenges remain before fully integrating them into daily industrial practices. Data privacy, integration costs, system interoperability, device comfort, and algorithmic bias must be addressed to ensure user acceptance and reliability. Looking ahead, ongoing innovation and interdisciplinary research hold promise for overcoming these obstacles. As industrial digitalisation advances, smart wearable devices will play an increasingly vital role in future factories, helping to create safer, more efficient, and more human-centric workplaces.

References

[1] D. Naranjo et al., “Wearable Sensors in Industrial Ergonomics: Enhancing Safety and Productivity in Industry 4.0,” Sensors, vol. 25, no. 5, p. 1526, 2025.

[2] E. Stefana et al., “Wearable Devices for Ergonomics: A Systematic Literature Review,” Sensors, vol. 21, no. 6, p. 1856, 2021.

[3] A. Motta et al., “The Use of Wearable Systems for Assessing Work-Related Risks,” International Journal of Environmental Research and Public Health, vol. 21, no. 12, p. 1567, 2024.

[4] M. Donisi et al., “Wearable Sensors and AI for Physical Ergonomics,” Diagnostics, 2022. [Online]. Available: https://pdfs.semanticscholar.org/88f8/c8c0a5870ef72c475622eeb89a9ccd54acf7.pdf

[5] R. Patel et al., “Industrial Wearables: A Survey on Technologies and Trends,” arXiv preprint, arXiv:2205.11740, 2022. [Online]. Available: https://arxiv.org/abs/2205.11740

[6] A. Babangida et al., “Sensor-Based Approaches to Biomechanical Risk Monitoring,” ACS Sensors, 2025. [Online]. Available: https://pubs.acs.org/doi/full/10.1021/acssensors.5c01578

[7] A. Doherty et al., “A Living Umbrella Review on Wearable Devices,” Sports Medicine, 2025. [Online]. Available: https://link.springer.com/article/10.1007/s40279-024-02077-2

[8] C. Pearl et al., “The Evolution and Future of Smart Wearables,” Nature Electronics, 2025. [Online]. Available: https://arxiv.org/abs/2502.05797

[9] A. Abdollahi et al., “Review of Smart Insoles for Industrial Biomechanics,” Applied Ergonomics, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0003687024000279

[10] J. Moon and Y. Ju, “Wearable Sensors for Healthcare of Industrial Workers: A Scoping Review,” Human Factors and Ergonomics in Manufacturing, 2024. [Online]. Available: https://www.researchgate.net/publication/384495159

[11] R. Sabino et al., “Wearables for Ergonomic Risk Assessment in Healthcare Workplaces,” Applied Ergonomics, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S016981412400026X

[12] B. Peters, “Task Classification via Wearables in Load-Handling Contexts,” Ergonomics, 2025. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00140139.2025.2486193