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Commentary

# Ergonomics in Industry 4.0: Human-Centered Approaches to Smart Manufacturing

**Tian Song***

*Department of Human Factors, Dong-Eui University, Busan, Republic of Korea*

## DESCRIPTION

The fourth industrial revolution-characterized by cyber-physical systems, internet of Things connectivity, artificial intelligence, and advanced robotics-is fundamentally transforming manufacturing environments worldwide. These technological advances promise unprecedented productivity, quality, and flexibility gains, yet their implementation often proceeds with insufficient attention to human factors. This commentary explains the evolving role of ergonomics in Industry 4.0 settings, arguing that human-centered approaches remain essential for realizing the full potential of smart manufacturing technologies.

The prevailing narrative surrounding Industry 4.0 often emphasizes technological capabilities while positioning human workers as either obstacles to automation or passive recipients of technological change. This technology-centric perspective overlooks the substantial evidence that optimal performance emerges from complementary human-technology systems rather than complete automation. Even highly automated manufacturing environments require human intervention for exception handling, strategic oversight, maintenance operations, and continuous improvement activities. These residual human roles often involve greater cognitive complexity and decision-making responsibility than pre-automation work, demanding careful ergonomic consideration. Physical ergonomics in Industry 4.0 environments presents both opportunities and emerging challenges. Collaborative robots and intelligent lifting devices can dramatically reduce physical loading during material handling and assembly operations. However, these technologies introduce novel interaction patterns requiring attention to clearance zones, communication interfaces, and emergency control access. Wearable technologies including exoskeletons and augmented reality devices may mitigate specific physical demands but introduce new loading patterns and physical constraints requiring systematic evaluation rather than presumptive implementation.

Cognitive ergonomic considerations become increasingly critical as manufacturing environments grow more complex. Workers must monitor multiple automated systems simultaneously, interpret increasingly sophisticated data visualizations, and make high-consequence decisions under time pressure. Interface design dramatically affects situation awareness and error rates in these contexts. Research demonstrates that displays emphasizing pattern recognition over raw data values, providing appropriate automation transparency, and supporting projection of future system states significantly improve operator performance compared to conventional interfaces.

The temporal distribution of workload presents particular challenges in highly automated environments. Extended periods of monitoring punctuated by sudden high-demand intervention requirements create cognitive demands fundamentally different from traditional manufacturing work. This irregular loading pattern interacts with vigilance limitations and skill degradation concerns, potentially creating new vulnerability patterns that must be addressed through both technical system design and organizational policies regarding rotation, training, and staffing levels.

Implementation approaches significantly influence ergonomic outcomes in Industry 4.0 transformations. Organizations adopting participatory technology implementation-actively involving operators in assessing requirements, evaluating alternatives, and refining configurations-report significantly higher acceptance rates and performance outcomes than those imposing technological changes from above. Training paradigms require fundamental reconsideration in Industry 4.0 environments. Traditional task-based training becomes rapidly obsolete as systems evolve, while purely theoretical instruction fails to develop the tacit knowledge required for effective operation. More effective approaches combine conceptual understanding of system principles with scenario-based practice emphasizing anomaly management rather than routine operation. This training methodology develops adaptive expertise that transfers more effectively across system upgrades and exceptional situations.

Organizational ergonomics-addressing work structures, communication patterns, and responsibility allocation represents

**Correspondence to:** Tian Song, Department of Human Factors, Dong-Eui University, Busan, Republic of Korea, E-mail: tiansong08@gmail.com

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an essential but often neglected dimension of Industry 4.0 implementation. Technical systems that enable flexible production must be complemented by equally adaptive organizational structures. Traditional hierarchical management approaches often prove insufficient for environments requiring rapid decision-making at the point of operation. Organizations successfully navigating this transition typically develop hybrid structures that combine clear strategic direction with substantial operational autonomy and cross-functional collaboration.

## CONCLUSION

Measurement frameworks for Industry 4.0 ergonomics must expand beyond traditional metrics to capture emerging dimensions of human-system performance. Comprehensive approaches include technical system performance (throughput, quality), human factors (workload, situation awareness), implementation outcomes (acceptance, utilization), and organizational impacts (skill development, job satisfaction). This multi-dimensional measurement approach helps identify synergistic optimization opportunities and avoid suboptimal tradeoffs between technical and human considerations.