

Digital Twin-Driven, Human-Centric Ergonomic Risk Forecasting in Manufacturing Assembly: Collective Case Study

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Abstract. Manufacturing and assembly often involve repetitive tasks, awkward postures, and strict time pressures, increasing the risk of work-related musculoskeletal disorders (WMSDs). Industry 5.0 emphasizes human-centered design, where Digital Twins (DTs) can improve safety without reducing productivity. However, current ergonomic approaches remain fragmented, relying on offline analyses or isolated real-time monitoring, with limited predictive, personalized, and adaptive capabilities for human–robot collaboration (HRC). This paper presents a collective case study of three automotive manufacturers that differ in terms of size, sector, digital maturity, and workstation organization. Cross-case and maturity analyses revealed four DT models: Model A (simulation-driven prevention), Model B (real-time adaptive ergonomics), Model C (personalized ergonomic forecasting), and Model D (a conceptual ideal integrating adaptivity and personalization). The models show how Digital Twins evolve from prevention to adaptivity, enabling early risk detection, flexible task adjustment, and inclusive design. While full Industry 5.0 integration is not yet realized, human-centric DTs promise safer, flexible, and ergonomic assembly systems.

Keywords: Digital Twin, Ergonomic Risk Forecasting, Human-Centered Design, Assembly Manufacturing, Industry 5.0.