Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p26336-cd

New challenges for Ergonomics & Human Factors in the Digital Transformation

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The current digital transformation in industrial manufacturing contexts presents significant challenges and opportunities for Ergonomics & Human Factors (E&HF). Considering that novel industrial environments are evolving towards interconnected, intelligent, and adaptive systems, ergonomists are increasingly required to co-develop solutions that align technological innovation with human well-being and performance. This paper summarizes two research projects (case studies) that exemplify this synergy between E&HF and digital transformation in different manufacturing workstations. The first case study explores augmented reality (AR) interfaces for training in industrial manufacturing settings. Through experiments involving usability tests, human performance, and cognitive workload metrics, the study assesses how AR can enhance skills acquisition while respecting ergonomic requirements. The second is focused on Human Robot-Collaboration (HRC), which addresses the ergonomic design of assembly tasks through adaptive cobots that respect workers' postures and physical factors. Results demonstrate improvements in musculoskeletal risk mitigation and human well-being, emphasizing the importance of ergonomic design of HRC scenarios. These projects illustrate the importance of E&HF methodologies for the design and development of the next generation of intelligent workstations. Globally, the results demonstrate that embedding E&HF across the digital transformation processes not only improves productivity and safety but also potentiates a more inclusive and sustainable technological evolution. Future research should advance toward real-time ergonomic adaptation, multimodal human monitoring, and explainable human-AI collaboration, respecting the paradigm of Industry 5.0.

Keywords: Ergonomics, Digital Transformation, Augmented Reality, Human-Robot Collaboration.

1. Introduction

The accelerating digital transformation in industrial manufacturing has highlighted the need for companies to design adaptive, efficient, and sustainable workstations, foreseeing human well-being and high-performance levels. Despite advances in automation and digitalization, many industrial settings still expose workers to excessive cognitive and physical demands (such as awkward postures, repetitive movements, and monotonous workflows), affecting workers' health and productivity (Meregalli Falerni et al. 2024) (Falerni et al., 2024; Monari et al., 2024; Varrecchia et al., 2023). Within the digital transformation, Ergonomics and Human Factors (E&HF) face unprecedented challenges and opportunities. Ergonomists are no longer peripheral evaluators but essential co-designers of technological innovation, ensuring that advanced automation, sensing, and decision-support systems are aligned with human capabilities, limitations, and well-being. This shift is aligned with the novel paradigm of Industry 5.0, which places the human at the center of technological systems, promoting sustainability, resilience, and efficiency (Cotta et al., 2021).

In this context, Human-Robot Collaboration (HRC) has emerged as one of the key enabling technologies for the manufacturing industry, presenting the potential to reduce physical workload, prevent work-related musculoskeletal disorders (WMSD), and improve both productivity and safety (Merlo et al., 2023; Varrecchia et al., 2023). HRC systems promise a synergistic combination of human cognitive flexibility and robotic precision. However, these systems also introduce new challenges for E&HF, especially in dynamic industrial conditions. For instance, ensuring that cobots adapt correctly to human postures, movements, and cognitive states remains a critical research topic, since inadequate robotic speed, proximity, or trajectory planning can increase cognitive workload and diminish perceived safety (Hostettler et al., 2025). In parallel, other studies highlighted relevant challenges, namely: the importance of considering the workers' needs and preferences (Falerni et al., 2024); adaptive task allocation based on real-time ergonomic assessment (Merlo et al., 2023); and collaborative assistance to reduce muscular activation and improve motor coordination during physically demanding tasks (Varrecchia et al., 2023). These advances demonstrate that, when ergonomics requirements are included from the design of collaborative systems, HRC can substantially enhance safety, reduce WMSD risk, promoting a human-centric digital transformation.

Parallel advances have emerged in ergonomics-driven digital interface design, raising several ergonomic concerns related to cognitive workload, attentional demands, and usability. For example, interfaces integrating augmented reality (AR) have been introduced to support industrial training and operational guidance. Previous studies, considering complex inspection and assembly scenarios, demonstrate that AR enhances task understanding, reduces cognitive demands, prevents human error, and improves skills acquisition when interfaces are designed according to E&HF principles (Ariansyah et al., 2024; Moghaddam et al., 2021; Marino et al., 2021). Despite these advantages, AR brings challenges for E&HF, namely that poorly designed interactions or excessive multimodal information can increase cognitive load and attentional demands, while tracking limitations may lead to awkward postures or constraints in workflow (Ariansyah et al., 2024).

The recent research outcomes focused on E&HF reinforce that the digital transformation requires an integrated approach of physical and cognitive ergonomics. While traditional ergonomic studies have focused predominantly on mitigating physical demands, recent studies in innovative and digital work contexts show that stress, attention, and cognitive workload are equally critical to ensure safe and effective human-machine interaction (Savković et al., 2026; Lagomarsino et al., 2023; Messeri et al., 2021).

As previously exposed, recent literature shows that the next generation of intelligent manufacturing systems shall integrate ergonomic principles since the earliest phases. The case studies presented in the current article corroborate this perspective by integrating ergonomic assessment of physical and cognitive factors, as well as demonstrating that human-centric design not only enhances productivity and safety but also supports a more inclusive and sustainable digital transformation. This assumption is aligned with the Industry 5.0 paradigm, foreseeing a digital transformation that empowers (not replaces) the human workers (Cotta et al., 2021). The actual article contributes to this ongoing program by presenting two research projects that illustrate the E&HF approaches to emerging digital solutions in manufacturing settings, namely: (i) AR interface for industrial training, analysing human performance and cognitive workload; and (ii) ergonomic redesign of assembly tasks through an adaptive HRC system.

2. Methodology

Our research was conducted by a multidisciplinary team from the Digital Transformation CoLab (DTx), in collaboration with the University of Minho (Portugal), integrating researchers of Ergonomics, Robotics, Design and Computer Vision. The two case studies (presented in section 3.) are focused on the manufacturing industry needs of industrial DTx partners. A multi-method human-centric methodology was adopted to ensure that technological development remained aligned with industry and workers' needs.

In the E&HF domain, the scientific literature presents several approaches validated for risk assessment of physical and cognitive factors (Lagomarsino et al. 2022; Colim et al. 2021). These methods and tools have been categorized according to the following headings (Figure 1): (i) Self-reports and checklists to collect workers' perceptions and/or to identify risk factors; (ii) Observational methods may be subdivided into simple and advanced techniques/methods; (iii) Direct measurements that rely on sensors that are attached directly to the workers for the measurement of the risk factors' effect on physiological and biomechanics parameters.

To assess participants' perceptions and the cognitive demands induced by the new digital solutions (AR and HRC), validated questionnaires were applied, namely: (i) NASA Task-Load Index (NASA-TLX) to measure cognitive workload (Hart, 2006); (ii) the Category Ratio-10 (CR-10) scale to measure perceived physical exertion (Borg, 1990); and (iii) Human Trust in Automation (HTA) (Jian et al., 2000) (the last two questionnaires mentioned were applied only in the HRC case). In the AR case study, the System Usability Scale (SUS) was also applied (Brooke, 2022), and complementary human performance indicators (e.g., task completion time and number of errors) were obtained through time-motion studies and direct observation.

For the HRC scenarios, different direct measurements were applied. For instance, physical ergonomic parameters were measured using: (i) wearable Inertial Measurement Units (IMU) to quantify Rapid Upper Limb Assessment (RULA) score (Colim et al., 2021; McAtamney & Corlett, 1993); and (ii) surface electromyography (EMG) considering muscles of the participants' dominant side recruited during the assembly tasks (e.g., right *Deltoideus anterior* and *Flexor carpi radialis*), respecting SENIAM guidelines (SENIAM.org, n.d.). These EMG data were collected by an 8-channel biosignals Plux HUB (Plux Wireless Biosignals Technologies, Lisbon, Portugal), and normalized using the Maximum Voluntary Contraction (MVC). Relatively to the IMU-based data, an upper-body MVN motion capture system (XSens Technologies B.V., Enschede, The Netherlands) was used.

In addition, cognitive measures included eye-tracking by Tobii Pro Glasses 3 (Tobii AB, Stockholm, Sweden) (e.g., analysing percentage of fixations in the handover region), and Electrodermal Activity (EDA) (phasic peaks per minute) by Shimmer 3 (GSR+) sensor (Shimmer Sensing, Dublin, Ireland).

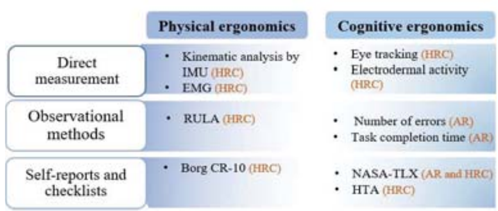

Fig. 1. Summary of the ergonomic methods and tools applied across the case studies focused AR and HRC scenarios.

In the first case study, we analysed an AR solution for industrial training (previously designed in Alexandre et al., 2025). In this project, the E&HF assessment focused on comparing the AR solution developed with the traditional paper-based training method (Figure 2). Twenty-nine participants completed the simulated industrial task under both training conditions, allowing analysis of performance indicators (task time, errors), cognitive workload, and usability. The task consisted of a set of machine setup operations in a Homag, existing in industrial scenarios of furniture manufacturing. For the ergonomic assessment of the AR solution, a machine prototype was created (Figure 2).

Fig. 2: Machine prototype and participant using the AR solution.

Regarding the HRC research project, we compared different groups of cobot behaviours, distinguishing between: (i) Ergonomic behaviours, in which the cobot acted proactively, adapted its handovers to the worker's posture and anthropometry, and complemented its actions with verbal transparency; and (ii) Non-ergonomic, in which the cobot followed fixed handover positions, only efficiency-based. Along with this research, several experimental tests were performed involving a global sample size of 38 participants. The ergonomic assessment combines cognitive and physical ergonomic outcomes, supported by multimodal data.

Inspired by a real-industry assembly task of window frames (as exposed in a previous publication of our team, Cardoso et al., 2025), a HRC prototype (Figure 3) was created, including a cobot – Kuka LBR 14 R820 collaborative robotic arm (©KUKA Augsburg, Germany) equipped with a two-finger gripper from Robosoft.

Fig. 3. Experimental apparatus of the HRC case.

All procedures involving human participants adhered to ethical and legal standards. Participants provided informed consent before data collection, in accordance with the University of Minho's Social and Human Sciences Ethics Committee (approvals CEICSH 038/2020 – HRC study and CEICSH 073/2023 – AR study) and following the principles of the Declaration of Helsinki.

Along with our projects, a participatory ergonomics strategy (Guimarães et al., 2015) was employed throughout the digital transformation of each use case, ensuring that workers, supervisors, and other industrial stakeholders contributed actively from the earliest design iterations to the final phases. This participatory involvement helped refine prototypes, identify practical usability constraints, and ensure that the proposed digital solutions would be acceptable, effective, and ergonomically adequate in real manufacturing contexts.

3. Results and discussion

3.1. Case study 1 – AR for industrial training

The NASA-TLX results reveal a consistent reduction in cognitive workload when the task was performed using the AR solution. Median mental demand decreased from 30.0 (paper) to 27.5 points, while temporal demand and perceived performance showed similar improvements (22.5 to 17.5 in both cases). Effort and frustration were also notably lower in the AR solution, reducing from 35.0 to 25.0 and from 20.0 to 12.5, respectively. Physical demand remained unchanged across conditions (10.0). In addition, according to participants' perceptions reported through the SUS questionnaire, the AR solution presents good usability (mean score of 75.1). Considering observational metrics, although task completion time was longer with the AR solution (mean time of 5.80 min *versus* 3.45 min) – probably due to limited prior exposure to this technology – the number of errors was lower, since the first interaction (38 operational errors with the AR solution *versus* 48 errors in the traditional condition). This aligns with prior studies showing that AR enhances accuracy and learnability, even when initial interaction is more time-consuming (Ariansyah et al., 2024).

Overall, the results indicate that the AR solution offers clear cognitive and performance advantages aligned with findings in previous studies showing that AR reduces visual search, improves information clarity, and supports task comprehension (Ariansyah et al., 2024; Marino et al., 2021).

3.2. Case study 2 – HRC for assembly tasks

In this research project, we studied how different cobot behaviours (ergonomic versus non-ergonomic) influence human physical and cognitive workload, as well as human performance (considering the task completion time) and trust during collaborative assembly. A summary of results across E&HF measures, comparing these behaviours, is presented in Table 1.

From a cognitive ergonomics perspective, NASA-TLX results demonstrated that ergonomic cobot behaviours (adaptive handover and verbal transparency) generally provided the most favourable experience, with a lower score for the mental demand perceived.

These findings are consistent with previous HRC studies showing that proactive assistance and clear communication can reduce perceived mental load and improve interaction fluency (Hostettler et al., 2025). Moreover, the human trust assessment clearly differentiated the cobot behaviours, highlighting the central role of cobot verbal transparency in fostering predictability and reliability perceptions. These results align with prior findings that transparency and communication are core determinants of trust in HRC, particularly when the robot's actions are autonomous or anticipatory (Hannum et al., 2023).

To complement these subjective measures, eye-tracking and EDA were used to assess cognitive workload and attentional dynamics. In the ergonomic condition, the proportion of visual fixations focused on the handover region increased, and visual search movements decreased, suggesting more predictable and less visually demanding interactions. This pattern is consistent with studies showing that more structured and transparent HRC behaviours lead to more focused eye-tracking patterns and reduced attentional dispersion (Lagomarsino et al., 2023; Hostettler et al., 2025). In addition, EDA results supported these trends, for example, phasic responses tended to be lower in the ergonomic HRC conditions, in line with Rajavenkatanarayanan et al. (2020).

Tab. 1. Summary of results (mean values) across measures comparing ergonomics and non-ergonomic cobot behaviours.

Measure	Non-ergonomic	Ergonomic
NASA-TLX Mental demand	10-13 points	5-7 points
Human trust	72-79%	90-91%
Eye-tracking (% fixations in handover region)	43%	62%
EDA (Phasic peaks/min)	1.3 peaks/min	0.8 peaks/min
Right arm flexion	21.3º	15.4º
Back flexion	21.7º	19.1º
RULA score	6 (high risk)	3 (low moderate risk)
EMG – Right *Deltoideus* anterior (%MVC)	22%	15%
EMG – Right *Flexor carpi radialis* (%MVC)	16%	10%
Borg CR-10 (Perceived exertion)	2.0 points	1.5 points

Relatively to the physical ergonomic assessment, IMU-based kinematic analysis and RULA scores demonstrated clear improvements in postural adoption during the collaborative assembly. The ergonomic cobot behaviours induced postures with joint angles closer to neutral ranges, resulting in lower RULA scores at the moment of handover (from a musculoskeletal high-risk level in non-ergonomic to a low-to-moderate risk level in ergonomic cobot behaviours). These findings are aligned with recent work demonstrating that skeleton-tracking or IMU-based adaptation can reduce postural deviations in collaborative assembly (Monari et al., 2024; Falerni et al., 2024)

EMG analysis of the upper limb muscles (e.g., *Deltoideus Anterior* and *Flexor Carpi Radialis*) confirmed a consistent reduction in muscle activation in the ergonomic conditions, indicating a reduced biomechanical load during handovers. Similar patterns of decreased muscle activation have been reported in dual-arm cobot material handling and other assisted tasks, where ergonomically optimized behaviours reduce muscular strain and fatigue (Varrecchia et al., 2023; Kim et al., 2019).

Self-reported physical exertion, measured with the Borg CR-10 scale, showed a non-significant reduction in the ergonomic behaviours. This outcome is coherent with other short-exposure ergonomic studies, where objective improvements in posture and muscle activity do not always translate into significant perceived differences (Savković et al., 2026). In summary, the multimethod results converge on the same conclusion: ergonomic cobot behaviours (combining anticipatory handovers, verbal transparency, and posture-based adaptation) lead to a better HRC from both cognitive and physical perspectives.

Globally, these results align with growing evidence that real-time ergonomic adaptation and multimodal human monitoring are essential for effective HRC. Prior studies show that posture-adaptive control reduces musculoskeletal risk (Monari et al., 2024) and that sensing-based adjustments to cognitive load improve trust and interaction fluency (Hostettler et al., 2025; Lagomarsino et al., 2023).

4. Conclusions

The present article demonstrates that the scientific area of E&HF is essential to guide the digital transformation of industrial manufacturing environments. Across two case studies – AR for industrial training and HRC for adaptive assembly – our findings show that human-centric design significantly improves cognitive and physical workload, trust, and human-machine interaction quality. AR training reduces mental and temporal demands while improving accuracy. On the other hand, ergonomic cobot behaviours reduce musculoskeletal risk and increase human well-being, including trust in this emerging technology. Overall, the findings reinforce that integrating E&HF from early design stages leads to safer, more sustainable, and more inclusive intelligent workstations, aligning with the human-empowerment vision of Industry 5.0 paradigm. Future developments should pursue real-time ergonomic adaptation, multimodal human monitoring, and explainable human–AI collaboration.

Acknowledgements

This research was supported under the base funding project of the DTx CoLAB - Collaborative Laboratory, under the Missão Interface of the Recovery and Resilience Plan (PRR), integrated in the notice 01/C05-i02/2022, which aims to deepen the effort to expand and consolidate the network of interface institutions between the academic, scientific, and technological system and the Portuguese business fabric. This work was also supported by FCT within Project I-CATER: Intelligent robotic Coworker Assistant for industrial Tasks with an Ergonomics Rationale, DOI 10.54499/PTDC/EEI-ROB/3488/2021.

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