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Towards an Ergonomic Assessment in Collaborative Robotic Systems: From Empirical Insights to Framework Development

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The transition from Industry 4.0 to Industry 5.0 marks a shift toward sustainable, resilient, and human-centered manufacturing. In this context, collaborative robots (cobots) are envisioned not as replacements for human labor but as intelligent partners capable of supporting workers through adaptive collaboration. However, most existing frameworks still treat ergonomics as a post-design outcome rather than a design and control requirement, and current cobots lack the ability to perceive, interpret, and adapt to human physical and cognitive states. Building upon a series of previous empirical studies, this work consolidates their findings into the Human-Centered Ergonomic Rational Assessment for Collaborative Robotic Systems (Human-ERA-Cobotic) framework, outlining a structured roadmap for integrating physical and cognitive ergonomics into the design rationale of cobots. The framework defines how ergonomic requirements can be systematically linked to adaptive cobot behaviors, promoting safety, fluency, and well-being in Human–Robot Collaboration (HRC). Instead of presenting a new empirical investigation, the current article synthesizes the results of previous studies, that collectively informed the three layers of the framework: (i) Ergonomic potentiality assessment, defining where and why HRC should be implemented; (ii) Ergonomic-based behavioral modes definition, identifying how assistance should adapt to human needs; and (iii) Real-time ergonomic assessment proposal, outlining how multimodal sensing of posture, attention, and task performance could enable adaptive control. By consolidating these contributions, the Human-ERA-Cobotic framework provides a conceptual roadmap for human-aware and ergonomically intelligent cobots, aligning technological innovation with the human-centered principles of Industry 5.0.

Keywords: Adaptive Assistance; Human-ERA-Cobotic Framework; Ergonomics; Human–Robot Collaboration; Industry 5.0.

1. Introduction

Global manufacturing is undergoing a profound transformation driven by the transition from mass production to mass customization, as markets increasingly demand personalized, high-quality products. This shift, however, exposes two major pressing challenges. The first concerns the unsustainable consumption of natural resources and the environmental impact associated with conventional production models (Lieder & Rashid, 2016). The second relates to the progressive aging of the working population, resulting from extended working lives and improved living conditions (Calzavara et al., 2020). Together, these ecological and demographic pressures highlight the urgent need for manufacturing paradigms that are not only more flexible and productive but also sustainable and human-centered.

Within this context, the Industry 5.0 paradigm redefines the role of technology in the manufacturing sector. Moving beyond the efficiency and automation-driven focus of Industry 4.0, Industry 5.0 emphasizes sustainability, resilience, and human-centered innovation (European Commission, 2021). Rather than replacing human labor, technology is envisioned as an enabler that enhances human capabilities, creativity, and well-being. A central element of this vision is Human–Robot Collaboration (HRC), where collaborative robots (cobots) are designed to safely share workspaces with humans and act as supportive partners rather than autonomous substitutes (Demir et al., 2019).

Cobots play a pivotal role in this transformation by combining robotic precision, endurance, and repeatability with human dexterity, perception, and decision-making (Gualtieri et al., 2021). Consequently, they are frequently proposed as solutions to reduce physical and cognitive workload in industrial environments (Cherubini et al., 2016). However, despite their increasing deployment, most cobot systems remain limited to repetitive and pre-programmed interactions. Their behavior is typically fixed and does not adapt dynamically to the worker's physical condition, cognitive state, or momentary performance (Villani et al., 2018). This limitation constrains the potential of HRC to truly support human well-being and undermines the human-centered vision of Industry 5.0.

From an Ergonomics and Human Factors (E&HF) perspective, this reveals a critical research gap. In most existing approaches, ergonomics is treated as a post-hoc evaluation tool rather than as a design and control requirement embedded within cobot reasoning (Cardoso et al., 2021). Moreover, cognitive and psychological dimensions of collaboration, such as mental workload, trust, transparency, and task fluency, remain insufficiently integrated into adaptive robotic control strategies (Gualtieri et al., 2021). Since ergonomics is a cornerstone of human-centered design, failing to incorporate it at the core of collaborative system design limits both the quality of interaction and the sustainability of human work (Zare et al., 2016).

Addressing these challenges requires cobots capable of perceiving, interpreting, and responding to human physical and cognitive states in real-time. This implies not only sensing human behavior, but also embedding ergonomic reasoning into the logic that controls cobot behavior and assistance. To respond to this need, this work proposes the Human-centered Ergonomic Rationale Assessment for Collaborative Robotic Systems (Human-ERA-Cobotic) framework. This framework synthesizes empirical evidence from multiple experimental studies into a unified conceptual structure that integrates physical and cognitive ergonomics into cobot design, behavior definition, and adaptive reasoning. By formalizing ergonomics as a guiding control principle rather than a mere assessment outcome, the proposed framework aims to advance the development of adaptive, human-aware collaborative robotic systems aligned with the principles of Industry 5.0.

2. Human-ERA-Cobotic Framework: Scope and Conceptual Rationale

This work presents the Human-ERA-Cobotic framework, a conceptual and empirically grounded approach that synthesizes evidence from multiple experimental studies conducted within the scope of the Intelligent Robotic Coworker Assistant for Industrial Tasks with an Ergonomics Rationale (I-CATER) project into a coherent ergonomic rationale for adaptive HRC. Rather than reporting a single experimental evaluation, the contribution of this paper lies in the integration and abstraction of empirical findings across different collaborative scenarios, interaction strategies, and ergonomic dimensions.

The framework formalizes ergonomics as a guiding principle for cobot design and behavior, moving beyond its traditional role as a post-hoc evaluation tool. It defines how ergonomic requirements should inform collaborative system design, behavioral logic, and adaptive reasoning, explicitly linking physical ergonomics, cognitive ergonomics, and task performance to cobot assistance strategies. As such, the Human-ERA-Cobotic framework does not constitute a ready-to-deploy control system, but rather a methodological and conceptual foundation for future adaptive HRC architectures.

Grounded in the principles of Industry 5.0, the framework emphasizes human-centered innovation, sustainability, and resilience. Consistent with the limitations of previous HRC frameworks, which have mainly focused on safety, task allocation, or post hoc ergonomic assessment rather than providing a structured basis for incorporating E&HF requirements into adaptive robotic control (Cardoso et al., 2021), it proposes a conceptual structure to support the future integration of workers' physical and cognitive states into cobot behavior adaptation.

3. Framework Architecture and Layers

3.1. *Overview of the Three-Layer Architecture*

The Human-ERA-Cobotic framework is organized into a three-layer architecture that defines how ergonomic reasoning should be systematically embedded across the design, interaction, and adaptation stages of HRC. Rather than treating ergonomics as an isolated evaluation activity, the framework conceptualizes it as a continuous reasoning process that guides both strategic design decisions and real-time cobot behavior. Each layer represents a distinct yet interdependent dimension of this process, collectively forming an ergonomic reasoning cycle.

The three layers are structured to reflect the progressive integration of ergonomic requirements into cobot systems. Layer 1 (L1) addresses design-time considerations by supporting the identification of tasks and workstations where collaborative assistance can provide meaningful ergonomic and operational benefits. Layer 2 (L2) translates these ergonomic requirements into behavioral principles that define how a cobot should assist the human worker during interaction. Layer 3 (L3) establishes the conceptual rationale for real-time ergonomic assessment and adaptive reasoning, enabling the system to interpret human physical, cognitive, and performance states and adjust its behavior accordingly.

A defining characteristic of the framework is the bidirectional flow of information between layers. In a top-down direction, ergonomic requirements and behavioral modes defined during design and interaction planning (L1–L2) inform the initial configuration of cobot behavior. In a bottom-up direction, continuous ergonomic assessment at run time (L3) provides feedback that can refine interaction strategies, adjust assistance modes, and support iterative improvement of collaborative system design. This bidirectional coupling ensures that cobot behavior remains responsive to human variability and contextual dynamics rather than being rigidly predefined.

The layered architecture (Fig.1) is intentionally modular and technology-agnostic. While it specifies the ergonomic rationale that should guide perception and control, it does not prescribe a specific implementation or control algorithm. This design choice allows the framework to be transferable across different industrial contexts and robotic platforms. At the same time, the framework assumes that ergonomic indicators can be captured through non-intrusive sensing approaches, such as RGB-D vision systems, to ensure scalability and industrial feasibility.

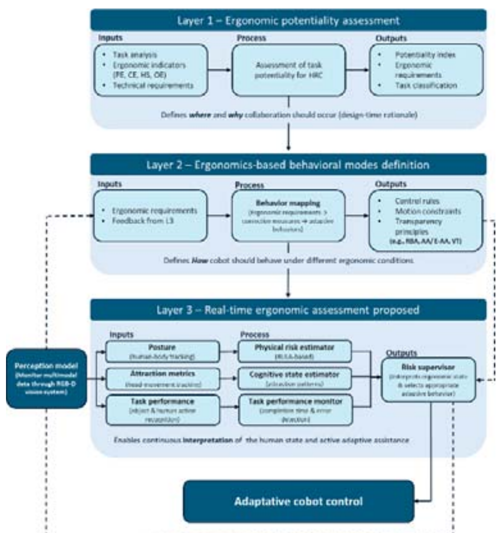

Fig.1. Human-ERA-Cobotic Framework Architecture.

3.2. *Layer 1: Ergonomic Potentiality Assessment*

L1 constitutes the strategic foundation of the Human-ERA-Cobotic framework and addresses the identification and characterization of tasks that are suitable for HRC (Cardoso, Colim, et al., 2025). Importantly, L1 does not address human–robot task allocation, but rather identifies tasks with sufficient ergonomic and operational potential for HRC. This layer operates as a decision-support mechanism that guides where and why cobot assistance should be introduced, ensuring that HRC deployment is ergonomically justified and operationally feasible.

L1 integrates physical and cognitive ergonomics, occupational health and safety considerations, and operational efficiency requirements with the technical constraints associated with cobot deployment. By adopting a multimethod assessment approach, this layer enables a comprehensive evaluation of workstation conditions, capturing multiple ergonomic, organizational, and process-related dimensions. The use of multimethod approaches is strongly recommended in ergonomics research, as it enhances assessment reliability and supports a holistic understanding of complex work systems (Boumann et al., 2023).

Within this layer, tasks are classified according to a potentiality index ranging from 0 (no potential) to 4 (high potential), reflecting the degree to which collaborative assistance could meaningfully improve ergonomic conditions and task performance. The outputs of L1 include: (i) the classification of tasks based on their relevance and suitability for HRC; (ii) the identification of human- and process-related limitations that should be addressed during collaborative redesign; and (iii) the definition of ergonomic and technical requirements that guide workstation layout, cobot selection, and interaction design (Cardoso, 2026)

By framing ergonomics as a prerequisite for collaboration rather than an outcome assessed after implementation, L1 ensures that downstream design and control decisions are grounded in validated ergonomic needs. As such, this layer establishes the contextual and methodological basis upon which the remaining layers of the Human-ERA-Cobotic framework are constructed.

3.3. *Layer 2: Ergonomic-based Behavioral Modes*

L2 translates the ergonomic requirements identified in L1 into ergonomic-based behavioral modes that define how a cobot should assist the human worker during collaboration. This layer bridges the gap between static ergonomic guidelines and the behavioral logic required for adaptive robotic assistance, formalizing how ergonomic principles can be operationalized through interaction design (Cardoso, 2026).

Although behavioral modes are initially defined during the interaction design phase, they are conceived as flexible and evolutive constructs rather than fixed control strategies. This design philosophy aligns with current research emphasizing that collaboration fluency, safety, and acceptance depend not only on mechanical precision, but also on the cobot's ability to modulate autonomy, anticipation, and communication based on the human's physical and cognitive state (Arvanitis et al., 2023; Hostettler et al., 2024; Messeri et al., 2021).

Within this framework, four primary ergonomic-based behavioral modes are defined: (i) Request-based Approach (RBA), in which the cobot acts only upon explicit human commands, preserving worker autonomy; (ii) Anticipatory Approach (AA), where the cobot predicts human intentions and proactively performs supportive actions; (iii) Verbal Transparency (VT), in which the cobot communicates its intent verbally to enhance understanding, trust, and task fluency; (iv) Ergonomic Anticipatory Approach (E-AA), an extension of anticipatory behavior where handover height and trajectory are dynamically informed by RULA-based postural risk and individual anthropometry. Although the E-AA mode primarily targets physical ergonomics, it may also support cognitive ergonomics by delivering parts at an appropriate height and in the correct orientation, thereby reducing mental processing demands and potential errors during collaboration.

Empirical evidence demonstrates that these assistance and communication strategies have differentiated effects on physical workload, cognitive workload, trust, and performance (Cardoso, Arruda, et al., 2025; Cardoso, Bicho, et al., 2024; Cardoso, Colim, et al., 2024). In particular, ergonomically pre-informed anticipatory behavior has been shown to improve postural alignment and reduce muscular activation during collaborative tasks, reinforcing the value of embedding ergonomic reasoning into cobot motion design (Cardoso, 2026).

While these behavioral modes can be defined offline during system configuration, L2 explicitly anticipates their refinement through feedback provided by real-time ergonomic assessment – L3. This iterative coupling between human monitoring and behavioral modulation supports human-in-the-loop interaction design, enabling cobot behavior to evolve dynamically in response to human variability and task context (Falerni et al., 2024; Monari et al., 2024).

3.4. Layer 3: Real-time Ergonomic Assessment Proposed

L3 represents the adaptive reasoning core of the Human-ERA-Cobotic framework and addresses one of the central challenges in HRC: the real-time assessment and interpretation of human physical, cognitive, and performance states. This layer defines the ergonomic rationale required to inform perception and decision-making modules in future adaptive HRC systems (Cardoso, 2026).

The architecture of L3 comprises four interconnected modules: (i) a physical risk estimator, which computes postural risk using Rapid Upper Body Assessment (RULA)-based indices to infer physical workload; (ii) a cognitive state estimator, which analyzes attraction behavior, based on head movement patterns (such as fixation concentration, dispersion, and transitions) to infer cognitive workload and attentional focus; (iii) a task performance monitor, which evaluates task fluency through execution time and error detection; (iv) a risk supervisor, which integrates physical, cognitive, and performance indicators to prioritize adaptive assistance responses, such as adjusting assistance modes or activating verbal cues.

A central contribution of this layer is the proposal of a non-intrusive and scalable approach to real-time ergonomic assessment in collaborative environments. The framework prioritizes the use of RGB-D vision systems within a unified perception module, responding to industrial constraints that often limit the feasibility of wearable or marker-based solutions (Villani et al., 2018). This approach is supported by recent advances in vision-based perception for HRC (Alves et al., 2024; Salimi et al., 2025).

Within this vision-oriented paradigm, a set of key ergonomic variables amenable to computer vision extraction is defined. These include human body tracking for continuous RULA-based postural assessment, head-movement tracking to infer attentional focus and cognitive effort from attraction metrics (Lagomarsino et al., 2022, 2023), and object detection combined with human action recognition to monitor execution time and error occurrence (Salimi et al., 2025). The selection of these variables is grounded in prior research demonstrating the sensitivity of RULA to postural deviations (Vignais et al., 2013), its compatibility with vision-based data (Arvanitis et al., 2023), and its validation across industrial contexts (Joshi & Deshpande, 2019).Furthermore, empirical studies have shown that increased cognitive workload is associated with attentional narrowing and reduced attraction dispersion, supporting the use of attraction metrics as indicators of cognitive state (Gorin et al., 2024). Related to performance indicators, the adoption of execution time and error frequency as core performance metrics is well established in both ergonomics and HRC research (Lin & Lukodono, 2025; Lorenzini et al., 2023).

4. Mapping of Ergonomic Indicators to Adaptive Cobot Behaviors

The Human-ERA-Cobotic framework formalizes how ergonomic indicators can be translated into adaptive cobot behaviors, establishing a structured decision rationale that links human state assessment to robotic assistance. This mapping represents a core contribution of the framework, as it operationalizes ergonomic knowledge into actionable principles capable of informing adaptive control strategies in human–robot collaboration (Cardoso, 2026).

Rather than prescribing a fixed controller, the framework defines how physical, cognitive, and performance-related indicators should be interpreted to modulate cobot behavior in a manner that preserves human well-being, task fluency, and worker autonomy. This approach aligns with recent research emphasizing that adaptive HRC systems must dynamically adjust motion, communication, and timing strategies based on sensor-derived indicators of human state (Falerni et al., 2024; Hostettler et al., 2024; Messeri et al., 2021).

Within the Human-ERA-Cobotic framework, adaptive behavior is governed by three main ergonomic input domains: physical ergonomics, cognitive ergonomics, and task performance. Each domain contributes complementary information that informs the selection or modulation of the behavioral modes defined in L2.

From a physical ergonomics perspective, postural risk indicators derived from RULA-based scores are used to detect deviations from neutral posture over time. When elevated postural load or sustained joint deviation is identified, the cobot adapts its behavior to reduce biomechanical strain. Typical adaptive responses include adjusting handover height, modifying object orientation, or altering motion trajectories to promote neutral alignment and reduce reach distance. Conversely, when posture remains stable and aligned, the cobot preserves its current behavior, maintaining task fluency and avoiding unnecessary intervention. This adaptive principle is grounded in the well-established relationship between non-neutral postures and increased risk of WMSD (McAtamney & Nigel Corlett, 1993) and reflects empirical evidence showing that ergonomically informed motion design improves postural quality and muscular activation during collaborative tasks (Cardoso, 2026).

From a cognitive ergonomics perspective, attraction metrics are used to infer attentional focus and cognitive workload. When indicators suggest attentional narrowing or elevated cognitive demand, the cobot compensates by increasing guidance and transparency. This may involve simplifying task sequences, reducing motion speed, or providing short verbal cues to enhance clarity and predictability. When cognitive load remains low and attention is balanced, the cobot preserves worker autonomy by maintaining its current assistance level. This adaptive principle reflects empirical findings demonstrating that anticipatory behavior and transparent communication can significantly reduce cognitive workload while fostering trust and smoother coordination (Cardoso, 2026). These results are consistent with previous studies showing that predictable motion, proactive assistance, and verbal transparency reduce uncertainty and improve collaboration fluency in HRC (Kluy & Roesler, 2021). Moreover, adaptive speed modulation has been shown to balance safety and cognitive effort, supporting sustained situational awareness during demanding tasks (Hostettler et al., 2024).

From a task performance perspective, execution time and error occurrence are monitored as indicators of fluency and coordination quality. Prolonged completion times or task deviations reflect increased physical fatigue, elevated cognitive demand, or breakdowns in human–robot coordination. In such cases, the cobot adapts its temporal behavior by adjusting delivery pace, introducing micro-pauses, or providing corrective verbal or visual feedback. When performance remains stable and error-free, the system maintains its timing and rhythm, reinforcing confidence and efficiency. This adaptive principle is supported by empirical evidence showing that increased errors and longer execution times are associated with higher cognitive workload and reduced collaboration efficiency (Cardoso, 2026). It also aligns with prior research demonstrating that predictive and anticipatory assistance improves task performance by reducing execution time and mitigating workload (Nemlekar et al., 2021).

Together, these adaptive principles define the decision logic through which real-time ergonomic assessment informs cobot behavior. L3 continuously interprets physical, cognitive, and performance indicators and activates the most appropriate behavioral mode defined in L2, ensuring that assistance remains proportional, context-aware, and human-centered. Importantly, adaptation is conceived as selective rather than continuous: the system intervenes only when ergonomic indicators exceed predefined thresholds, preserving human autonomy and avoiding over-assistance.

5. Conclusions

This paper presented the Human-ERA-Cobotic framework, a conceptual and empirically grounded approach that positions ergonomics as a guiding principle for adaptive HRC. By integrating physical ergonomics, cognitive ergonomics, and task performance within a unified reasoning structure, the framework moves beyond post-hoc assessment and links human state monitoring directly to cobot behavior modulation.

The three-layer architecture provides a coherent rationale connecting design-time decisions with run-time adaptation, addressing the fragmentation commonly observed between ergonomic evaluation and robotic control in

HRC. By defining how ergonomic indicators can inform adaptive assistance strategies, the framework contributes a methodological foundation for the development of human-aware and ergonomically intelligent collaborative robotic systems.

While the framework has been tested and proposed at the layer level under controlled laboratory conditions, full closed-loop implementation and real-time adaptive validation remain future work. Ongoing research will focus on system-level integration using non-intrusive, vision-based sensing, the development of adaptive decision models, and broader validation across diverse tasks and realistic industrial settings, in line with the principles of Industry 5.0.

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