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Review article

Research Directions for Ergonomic Challenges in Collaborative Human–Robot Workplaces

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ABSTRACT

The integration of collaborative robots into shared workspaces introduces new ergonomic challenges beyond traditional automation. This study provides an integrative synthesis of research on ergonomics in human–robot collaboration, identifying key factors, limitations, and research directions. The results show that ergonomics in collaborative workplaces is a multidimensional and system-level issue, involving physical, cognitive, and organizational aspects. While cobots can reduce physical strain, they may simultaneously increase cognitive and coordination demands. The study highlights the need for integrated, adaptive, and human-centered approaches to support safe and effective collaboration in real industrial environments.

Key words: *workplace design, collaborative workplace, collaborative robot, ergonomics;*

1. INTRODUCTION

Human–robot collaboration (HRC) is a manufacturing paradigm in which humans and robots work together by combining their complementary strengths to achieve efficient, flexible, safe, and sustainable production [1]. Collaborative human–robot workplaces (CHRWs) are environments in which humans and robots share a workspace and interact directly during task execution, in contrast to traditional automation systems, where human and machine activities are spatially or temporally separated. This model has attracted growing interest in recent years due to several converging drivers. The growing interest in HRC is driven by the limitations of conventional manufacturing systems, increasing sustainability requirements, and rapid technological advances. Traditional automated systems often offer limited flexibility, whereas purely manual production remains constrained in terms of efficiency and consistency, creating a need for more adaptive production solutions. Beyond these operational considerations, pressures related to climate change, carbon neutrality, and resource efficiency have increased interest in HRC as an approach that may help reduce energy consumption, material waste, and operational inefficiencies. This transition is further reinforced by the development of smart manufacturing and Industry 5.0, both of which emphasize human-centered production supported by advanced digital and robotic technologies. As a result, HRC has emerged as one of the key paradigms reshaping modern manufacturing [1], and current research increasingly addresses issues such as task allocation, multimodal perception, human–robot interaction, digital twins, adaptive control, and human state modeling.

Within this research landscape, ergonomics is particularly important because it directly affects both worker well-being and overall system performance. In collaborative settings, ergonomics extends beyond physical workload

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and includes cognitive and organizational dimensions arising from close, dynamic, and technologically mediated interaction between humans and robots. Therefore, the design of human-centered CHRWs must integrate ergonomics, safety, usability, and worker well-being.

2. METHODS

This study adopts a structured literature review to identify, analyze, and synthesize research on ergonomics in HRC, focusing on key factors, challenges, and research gaps in collaborative human–robot workplaces (CHRW). In addition to a systematic search, the approach incorporates an integrative, narrative-informed synthesis, including both primary studies and higher-level evidence syntheses. This "review of reviews" perspective enables the consolidation of fragmented knowledge and supports the development of a coherent conceptual framework rather than exhaustive coverage.

The literature search was conducted using Scopus. The search terms combined concepts related to HRC (e.g., "human–robot collaboration", "collaborative robotics", "cobots") with terms associated with ergonomics and human factors (e.g., "ergonomics", "workload", "posture", "fatigue", "musculoskeletal disorders", "safety", "human factors", "digital twin", "task allocation"). The search process was iterative, with particular emphasis placed on review publications that helped refine the search scope and identify recurring thematic areas.

The review included peer-reviewed journal articles published in English between 2017 and February 2026. Studies were considered relevant if they explicitly addressed ergonomic or human-factor-related issues in HRC (addressed in title or abstract of the paper). Special interest was given to workplace-oriented studies, especially those concerning shared workspaces, coordinated tasks, safety-constrained interaction, and broader organizational or design implications. Studies offering integrative perspectives, such as conceptual frameworks, thematic syntheses, or comparative analyses, were also given particular attention. The selected literature was analyzed through qualitative thematic synthesis. Studies were iteratively compared and grouped in order to identify recurring themes and dominant areas of research. The analysis focused on: (1) types of ergonomic issues addressed in the literature, (2) ways of conceptualizing human–robot work systems, including task allocation, interaction design, safety, and organizational context, and (3) recurring patterns in reported outcomes, tensions, and trade-offs. This approach made it possible to provide a structured map of the field and to highlight directions for further research.

3. RESULTS

The research on collaborative human-robot workplaces increasingly treats ergonomics as a multidimensional problem involving physical load, posture, task allocation, workspace design, timing, and cognitive workload rather than only traditional posture scoring [2–7]. In addition, recent syntheses frame collaborative human-robot workplaces (CHRW) as socio-technical systems in which ergonomic risk and operational efficiency are co-created through interaction between the human, robot, task, and organizational context [8]. Reviews of industrial HRC consistently argue that safety, interface design, and work organization shape operator strain as much as robot presence [2, 3, 6]. Within this perspective, ergonomics is positioned not only as an evaluation domain but also as a system-level design and control variable [8].

Evidence across HRC and collaborative assembly studies suggests that cobots improve ergonomics when they take over forceful, repetitive, overhead, or extended-reach subtasks, especially in assembly and material-handling contexts [4, 5, 9, 10]. Case-study and design research on collaborative workstations reports reduced postural load when the robot supports physically unfavorable subtasks and the station is redesigned around the operator rather than added to an unchanged layout [5, 9]. At the same time, robotic assistance is typically applied to reduce specific load components rather than redesign the entire work system [11, 12].

At the same time, the literature does not support the claim that cobots always improve ergonomics. Several studies and reviews note that poor handover design, constrained shared spaces, robot-centered layouts, and mistuned timing can create new ergonomic burdens, including awkward trunk rotation, static waiting, visual monitoring demand, and compensatory movements [2, 4, 5, 7, 10]. In other words, safe collaboration does not automatically mean ergonomic collaboration [2, 3, 5]. This reinforces that safety and productivity must be jointly optimized, although safety constraints remain non-negotiable boundary conditions in system design [13, 14].

A strong research direction is human-aware task allocation: deciding which subtasks should be done by the human and which by the robot in order to reduce biomechanical risk while maintaining productivity [3, 7, 15, 16]. This line of work reveals that many risks originate not from the workstation alone, but from a poor division of labor [7, 15, 16]. Recent studies extend this toward dynamic and multi-criteria task allocation models, where decisions are adapted based on fatigue, workload, and system performance [17-19].

Another major direction is human-aware motion and handover planning. Research in this area incorporates ergonomic criteria such as joint load, reach, posture, or muscular effort into robot planning so that trajectories and handover points reduce human strain rather than only satisfying collision-avoidance or cycle-time requirements [10, 16, 20]. This is especially relevant in shared workspaces, where robot base location, path, and exchange position affect torso rotation, shoulder elevation, and reach asymmetry [4, 10, 16]. This reflects a shift from static workstation geometry toward interaction design based on trajectories and adaptive assistance parameters [12, 21].

The reviewed studies employ a wide range of ergonomic assessment methods, reflecting the multidimensional nature of human–robot collaboration (Fig.1). As summarized in Table 1, these methods span physical, cognitive, and environmental and safety ergonomics, and include standardized assessment tools, measurement-based techniques, and model-based approaches.

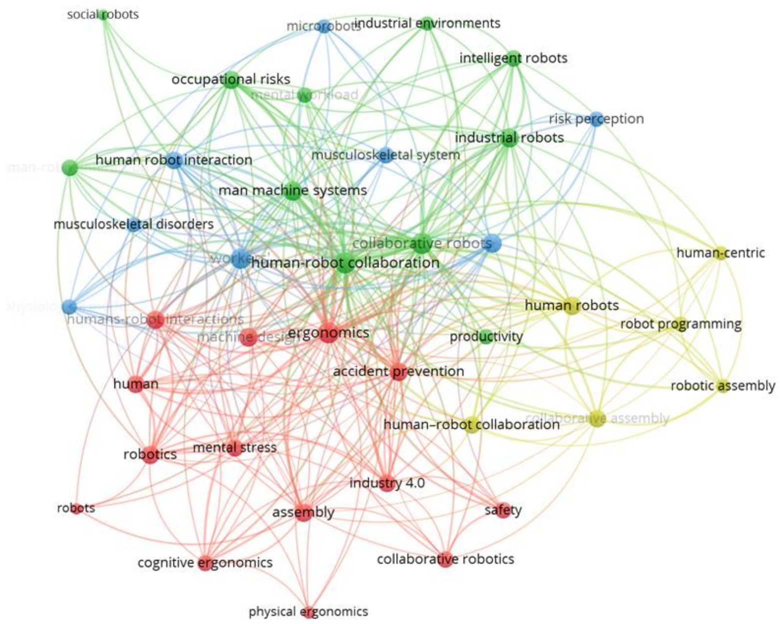

Fig. 1 *Visualization of the keyword co-occurrence network in ergonomics and human–robot collaboration research*

Table 1 – *Ergonomic assessment methods in HRC research*

Type of ergonomics		
Physical ergonomics	Cognitive ergonomics	Environmental & safety ergonomics
• RULA • REBA • OCRA • NIOSH • EAWS • Borg rating • EMG-based muscle activity assessment • Anthropometric reach envelope analysis • Wearable sensors (IMU-based)	• NASA-TLX (mental workload) • System Usability Scale (SUS) • Trust scales • Dual-task performance • Error rates (task accuracy and performance reliability) • Training time (learning efficiency and adaption) • Heart rate (physiological workload and stress) • EEG (brain activity and cognitive load) • Cortisol (stress response indicator)	• Noise level measurement (dB) • Illumination measurement (lux) • Thermal & environmental comfort surveys • Well-being ratings • Eye-tracking (visibility) • Visibility checklists • Safety envelope checks • Virtual safety boundaries • Force and torque measurement • Risk assessment (e.g., IEC 31010)

Physical ergonomics is primarily addressed through posture and biomechanical assessment methods, while cognitive ergonomics relies on subjective, behavioural, and physiological measures to capture mental workload and interaction quality. Environmental and safety ergonomics are evaluated through a combination of workplace condition measurements and safety verification approaches. Together, these methods illustrate that ergonomic evaluation in HRC is not limited to isolated indicators, but involves multiple complementary perspectives that capture both human performance and system conditions. In this context, the field is also moving toward real-time ergonomic monitoring, often using IMUs, motion capture, EMG, computer vision, or digital human models/digital twins to estimate operator risk during execution [6, 7 ,16, 20, 22]. These approaches can identify where strain emerges during specific subtasks, handovers, or production disturbances rather than only scoring a task after the fact [16, 20, 22]. More recently, this trend is evolving toward closed-loop systems, where psychophysiological and behavioral signals are integrated into the control loop, enabling adaptive robot behavior based on the operator's state [23, 24].

Recent ergonomics work in HRC also emphasizes that cognitive and psychosocial load matter. Reviews and empirical papers discuss workload, trust, predictability, loss of autonomy, and monitoring demands as key dimensions of HRC quality [2, 3, 6, 25]. This means an ergonomic assessment that looks only at posture may miss important human factors problems in collaborative cells [6, 25]. In this context, multimodal assessment approaches combining subjective (e.g., NASA-TLX) and objective physiological measures are recommended [24, 26].

Finally, a limitation in the literature is that many studies are based on short-duration lab tasks, small samples, or posture metrics, while fewer examine full-shift exposure, fatigue accumulation, or long-term outcomes in real industrial settings [2, 6, 7, 22]. Thus, the evidence base remains incomplete for long-term occupational risk [2, 6, 22]. Additionally, variability in real-world environments and human motion introduces challenges for measurement accuracy, requiring sensor fusion and more anatomically realistic modelling [27].

Based on [28-42], ergonomics in HRC is investigated predominantly through a physical ergonomics perspective, while cognitive ergonomics and its interaction with safety and performance receive less consistent attention. The most frequently examined factors include posture, repetitive movements, WMSD risk, force exertion, fatigue, reachability, and workload distribution [29-32]. These are typically evaluated using methods such as RULA, REBA, OCRA, Borg scales, motion capture, and digital human modelling [3, 30, 31, 33-35]. At the same time, there is growing emphasis on continuous and real-time assessment systems, including markerless motion capture and human pose estimation [43, 44].

In addition to physical factors, several studies address cognitive ergonomics, including mental workload, attention, trust, stress, visual monitoring, and auditory load [30, 31, 33, 35, 36]. These are assessed using NASA-TLX, eye-tracking, subjective evaluations, and behavioural analysis, confirming that ergonomics in HRC is inherently multi-dimensional [30, 31, 33, 36, 37]. Emerging research explores the integration of physiological sensing and AI models to enable adaptive human-robot interaction [24, 45].

A consistent finding is that physical ergonomics remains the dominant research focus [32, 36]. Multiple reviews confirm that cobots reduce physical strain when handling repetitive or demanding tasks [37, 38]. Case studies show improvements through task reallocation, layout optimization, and posture reduction [32, 38-40]. Digital twin-based approaches enable early evaluation of posture and safety conditions [39], while workstation parameters influence operator efficiency [38]. Recent developments extend toward human digital twins and federated models for adaptive decision-making [46, 47].

Several studies demonstrate that ergonomic improvements are linked to performance outcomes, indicating that ergonomics is also a productivity factor [34, 35]. However, cognitive ergonomics remains underrepresented [30, 31, 33]. Operators must monitor robots, divide attention, and interpret behavior, increasing mental demands [36, 37]. Visual and auditory conditions further influence workload and well-being [37], and differences between objective and perceived risk affect system acceptance [48, 49].

Another observation is that ergonomics and safety are often treated as related but insufficiently integrated domains [41, 42]. While safety focuses on collision avoidance and standards, ergonomics emphasizes posture and workload [29, 33]. Several studies emphasize joint consideration already in the design phase [33-35, 40]. This lack of integration can lead to suboptimal solutions. Recent research proposes safety architectures combining trajectory constraints, situational zoning, and sensor-based monitoring [14, 50].

The reviewed studies report recurring challenges, including awkward postures, repetitive tasks, fatigue, cognitive overload, and coordination demands [29, 30, 36-38]. Additional challenges include limited optimization models, lack of human variability, and insufficient real-time monitoring [29,30,33,39]. Many studies remain laboratory-based and lack industrial validation [30, 31, 33]. These challenges are amplified in non-standard environments such as agriculture or healthcare [51, 52].

From a methodological perspective, research is shifting toward digital twins, simulation, and sensor-based approaches enabling early ergonomic evaluation [30, 32, 34, 35, 39, 40]. However, most implementations remain static, with limited real-time adaptation [30, 33]. Future directions emphasize adaptive, human-state-aware systems supported by AI/ML and simulation [12, 21].

Overall, HRC can improve ergonomics, but only when treated as a core design requirement rather than a post-hoc metric [33]. Effective improvements require integrated approaches combining task allocation, workstation design, and simulation [32, 34, 35, 39, 40]. The main gap remains the lack of frameworks integrating physical ergonomics, cognitive ergonomics, safety, and performance in real-world environments [29-31, 33]. Addressing this requires holistic, adaptive, socio-technical approaches integrating human state modeling, real-time control, and organizational factors [8, 53]. Fig. 2 summarizes the key research areas in ergonomics for collaborative human–robot workplaces, emphasizing the multidisciplinary nature of ergonomic assessment and optimization in human–robot collaboration. This directly supports the motivation for the present research, which aims to further investigate ergonomic challenges in collaborative human–robot workplaces and contribute toward more holistic, human-centred HRC system design.

4. CONCLUSIONS

This study provides a structured overview of ergonomic challenges in CHRW, demonstrating that ergonomics in HRC cannot be reduced to physical workload alone, but must be understood as a multidimensional phenomenon encompassing physical, cognitive, and organizational factors.

The findings confirm that collaborative robots can improve physical ergonomics, particularly when performing repetitive and physically demanding tasks. However, these benefits depend on system design, especially task allocation, workspace configuration, and interaction dynamics.

At the same time, HRC systems may introduce new risks, particularly related to cognitive load, monitoring demands, and coordination in shared workspaces. This highlights that improvements in one dimension may involve trade-offs in others, requiring balanced, system-level design approaches.

The main contribution of this study is to position ergonomics not only as an evaluation domain but as a design and decision-making principle embedded within the collaborative system, supporting a shift toward more integrated approaches that consider interactions between human, robot, task, and organizational context. The integrative review approach enables the consolidation of fragmented and multidisciplinary knowledge and supports the identification of future research directions.

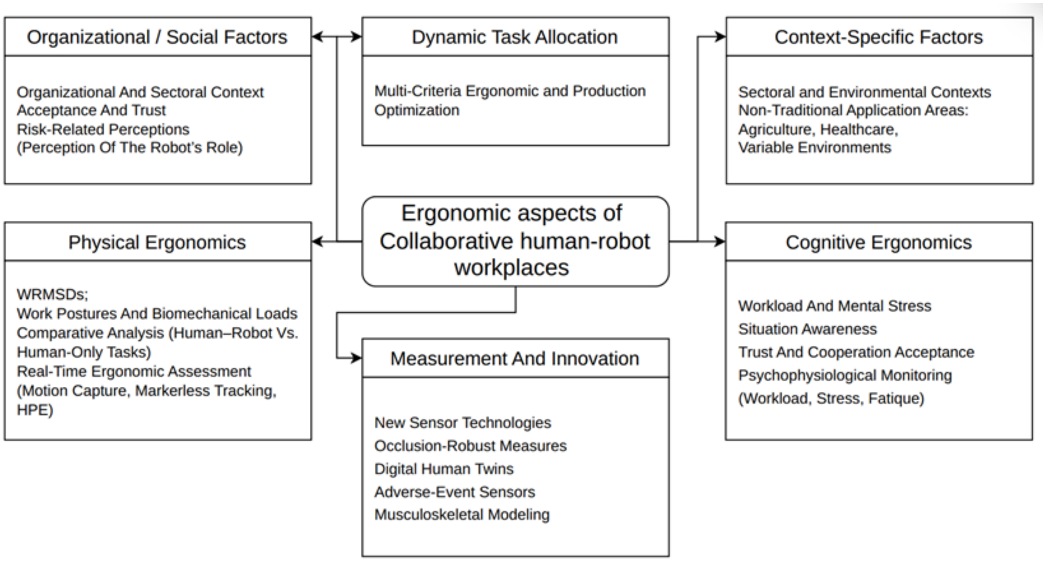

Fig. 2 *Research areas for ergonomics within collaborative human–robot workplaces*

The integrative review approach enables the consolidation of fragmented knowledge and supports the identification of future research directions. However, the study is limited by non-exhaustive coverage, potential database and selection bias, and the heterogeneity of included studies.

Overall, successful HRC implementation depends on balancing human well-being and system performance. The findings are particularly relevant for collaborative systems in manufacturing and related domains. Future research should focus on integrated, adaptive, and human-centered frameworks that better translate experimental findings into real industrial applications.

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