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Review

The role of human factors/ergonomics in the design and management of manufacturing human robot collaborative workstations adopting the industry 5.0 approach

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Abstract: As industries move towards greater integration of advanced robotics, the focus on human-centric approach promoted by Industry 5.0 becomes essential. One of the enabling technologies of Industry 5.0 is collaborative robotics. Nevertheless, the literature indicates that the aspect of the application of Human Factors/Ergonomics (HFE), in industrial collaborative robotics is an emerging and not yet consolidated research topic. For this reason, the aim of this research is to explore the current state of the art regarding the application of Human Factors/Ergonomics (HFE) in the design and management of human-robot collaborative (HRC) workstations in the manufacturing industry adopting the Industry 5.0 approach. A systematic literature review was conducted identifying a total of forty scientific journal articles that met the established inclusion criteria. It was found that the main research topics addressed by the reviewed literature are: Factors influencing the acceptance of cobots by human coworkers and managers, Methodologies and tools used for ergonomics assessment in HRC systems, Task allocation strategies, Technical and ethical guidelines for the design of HRC workstations, and Sustainability assessment in HRC configurations. All the findings of this study have been meticulously presented and discussed, and it is expected that they can guide academics and practitioners in designing and managing HRC workstations to make them more human-centered, sustainable, resilient, and efficient. The value of this article lies in the fact that the results have been analyzed from an industrial engineering perspective and can serve as a complement to studies on the subject carried out by robotics specialists.

Keywords: human factors/ergonomics, collaborative robotics, industry 5.0, manufacturing, collaborative robotic workstations design

1. Introduction

Sustainability of industrial processes is one of the drivers of the fifth industrial revolution and is defined as a multidimensional concept encompassing environmental, social and economic aspects. Industry 5.0 recognizes the power of industry to achieve societal goals beyond jobs and growth to become a provider of prosperity, by making production respect the boundaries of our planet and placing the wellbeing of the industry worker at the center of the production process [1].

Industry 5.0 should not be understood as a replacement nor an alternative to, but an evolution and logical continuation of the existing Industry 4.0 paradigm. The concept of Industry 5.0 is not based on technologies, but is centered around values, such as human-centricity, resilience and ecological or social benefits. It could also be described as re-introducing the lost dimension of a “human/value-centered Industry 4.0” [2].

For the aforementioned, manufacturing companies should consider the human element as their core and valuable part, improving working conditions and developing human-centered production systems. In this context, work-related Human Factors/Ergonomics (HFE) plays a key role, because it is concerned with the psychophysical and social well-being of operators [3].

Achievement of goal number 8 of the UN Millennium Development Goals for Sustainable Development, "Decent Work and Economic Growth", is dependent on the consideration of human factors/ergonomics. It is vital to pay close attention to HFE in design, as otherwise work systems will not support the sustainability of workers, organizations or societies [4].

Organizations must address issues related to worker safety, health, wellbeing, and sustainability, encompassing risks that range from musculoskeletal disorders to injuries caused by physiological, biomechanical, cognitive, psychological, and relational factors. These efforts are essential to manage the impact of introducing information technology, robotics, artificial intelligence, and digitalization into work systems [4].

Human-robot collaborative manufacturing has been proposed as a potential solution to improve workplace conditions. The European Union is contributing significantly to increasing effort in this field by recognizing collaborative robots (cobots) as one of the technologies that can positively influence the economy and society [5].

The industrial cobots, reduce ergonomic concerns that arise from on-the-job physical stress, and further improve workplace safety, quality, and productivity [6]; however, the inclusion of ergonomic criteria in the development and implementation of this technology is far from being well-known [7].

Cobots have largely replaced conventional industrial robots in today's workplaces, particularly in manufacturing setups, due to their improved performance and intelligent design. In the framework of Industry 5.0, humans are working alongside cobots to accomplish the required level of automation. However, human–robot interaction has brought up concerns regarding HFE [8].

From a physical point of view, robots can facilitate the reduction of biomechanical overload to operators in heavy and repetitive tasks. But this close collaboration could cause psychological stress to operators. In fact, the well-being and performance of operators may be affected by the unknown behavior of the robot. For this reason, although cognitive ergonomics is a very novel and often undervalued topic in the field of industrial collaborative robotics, it is also necessary to include these aspects in the design phase of collaborative work cells [9].

For all the above mentioned, the study of the role of HFE in Human-Robot collaborative (HRC) systems design and management is a fundamental parameter in industrial engineering to improve the efficiency and effectiveness of industrial processes. Nevertheless, the literature indicates that the aspect of the application of HFE in industrial collaborative robotics, is an emerging and attractive research topic whose study has not yet been consolidated [9]. The paucity of papers addressing the application of HFE to achieve worker well-being in HRC systems indicates an urgent necessity for further research on this topic [10]. This is the gap that the present study seeks to fill.

Therefore, the aim of this research is to explore the current state of the art regarding the application of HFE in the design and management of HRC workstations in the manufacturing industry adopting the industry 5.0 approach.

To achieve the objective of this research, the following questions should be answered:

RQ1: What has been the annual performance of the literature on the application of HFE in the design and management of HRC workstations adopting the industry 5.0 approach in the last five years?

RQ2: What is the context of research on applying HFE to design and manage HRC workstations adopting the industry 5.0 approach?

RQ3: What are the main research topics that researchers are currently addressing in scientific literature, regarding the application of HFE in the design and management of HRC workstations adopting the industry 5.0 approach?

The remainder of the article is organized as follows: In Section 2, the definitions of the main theoretical concepts used in this study and a conceptual framework to understand how the application of HFE contributes to the design and management of manufacturing HRC workstations to meet Industry 5.0 objectives are presented. In Section 3, the research methodology is described. In Section 4, the results of the systematic literature review conducted are presented. In Section 5, the discussion and critical analysis of the results obtained are presented. In Section 6, the conclusions, future directions, and limitations of the study are provided.

2. Theoretical background

This section presents the definitions of the main theoretical concepts used in this study. Based on these concepts, a conceptual framework was constructed to understand how the application of HFE contributes to the design and management of manufacturing HRC workstations to meet industry 5.0 objectives.

2.1. Human factors/ergonomics

Human Factors/Ergonomics (HFE) is the scientific discipline concerned with the understanding of interactions among human and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance [11].

Ergonomics is classified into physical, cognitive, and organizational ergonomics. Physical ergonomics is concerned with human anatomical, anthropometric, physiological and biomechanical characteristics as they relate to physical activity. Relevant topics include working postures, materials handling, repetitive movements, work-related musculoskeletal disorders, workplace layout, physical safety and health. Cognitive ergonomics is concerned with mental processes, such as perception, memory, reasoning, and motor response, as they affect interactions among humans and other elements of a system. Relevant topics include mental workload, decision making, skilled performance, human-computer interaction, human reliability, work stress, and training as these may relate to human-system design. Organizational ergonomics is concerned with the optimization of sociotechnical systems, including their organizational structures, policies, and processes. Relevant topics include communication, crew resource management, work design, design of working times, teamwork, participatory design, community ergonomics, cooperative work, new work paradigms, virtual organizations, teleworking, and quality management [12].

2.2. Work-related musculoskeletal disorders

Work-related Musculoskeletal disorders (WMSD) are defined as a set of painful inflammatory and degenerative conditions affecting the joints, spinal discs, cartilage, muscles, tendons, ligaments, and peripheral nerves. The origin of these disorders is frequently associated with physical risk factors of manual handling such as repetitive movements of body parts, heavy lifting, and awkward postures, and they are one of the main occupational health problems and a major cause of occupational absenteeism and decreased productivity [5]. According to the European Agency for Safety and Health at Work (EU-OSHA), approximately three out of five workers suffer from a WMSD [13]. Ergonomic interventions are key to preventing WMSD. The ergonomic intervention aims to redesign the workstation and process to improve health, safety, and productivity [14].

2.3. Cognitive workload

"Cognitive load" is the mental effort required to perform a task [15]. Research shows that excessive cognitive demand at work can negatively impact health and performance, renewing focus on cognitive load theory [13].

2.4. Ergonomics assessment in the industrial environment

According to [16,17], there are three methods to assess the physical workload a worker is exposed to at their workplace: 1) Subjective judgements: self-questionnaires from workers or narrative interviews from experts; 2) Systematic observations: collected on-site at the workplace or from video recordings; 3) Direct measurements: performed on-site at the workplace or during simulations in laboratories. This method inevitably implies a sensor system due to the required accuracy and online availability of the measurements [13].

We can distinguish two types of physical exposure: external and internal exposure. External exposure refers to the work environment and the actual working method, i.e. adopted postures, executed movements, and exerted forces that workers exploit to perform an activity with their anthropometric characteristics. The corresponding moments and forces within the human body are, instead, referred to as internal exposures. Subjective judgements and Systematic observations are determined to tackle external exposure. On the other hand, Direct measurements can be employed to estimate internal exposure [18,19]. The ergonomics assessment can then be extracted directly from the collected data or estimated by integrating them within ad-hoc models. The same categorization may be applied for cognitive load measurements [13].

2.5. Human-robot collaboration

Human-robot collaboration is one of the main technologies of Industry 4.0 and is currently changing the development of activities in the production plants of manufacturing companies [8,20–22].

Collaborative robots (cobots) are innovative industrial technologies introduced to assist operators in performing manual activities in so-called cyber-physical production systems. One of the main uses of cobots will be to support humans in the most stressful physical activities by reducing work-related biomechanical overload, especially in manual assembly activities [23].

Cobots, work side by side with humans to perform a task or series of tasks [24]. The use of a "cobot" will reduce the number of tasks to be performed by a worker and improve the quality and productivity of a process [25].

Cobots are a sub-type of robots specially tailored to work in close proximity to humans or other robots. Through a closer interaction between the machine and the operator, it enables collaborative scenarios where the continuous accuracy, speed, and repeatability typical of robots can be combined with the innate adaptability, dexterity, perception, and intelligence distinctive of humans [6,26,27]. Manufacturing companies introduced cobots in production environments to increase productivity, usability, and flexibility. In the manufacturing sector, cobots assist workers with tasks that are ergonomically challenging. Studies indicate that cobots can significantly improve productivity by automating repetitive tasks while allowing human workers to focus on more complex activities that require cognitive skills [28,29].

The evolution of industrial robotics has been a gradual process from Caged robots to Human-Robot Teaming (HRT) [30]. The pinnacle of robotics evolution is Human–Robot Teaming (HRT). In this advanced stage, robots are integrated into human teams as equal partners rather than mere tools. HRT demands sophisticated AI and machine learning algorithms that enable robots to adapt to human behaviors, preferences, and decision-making processes [31].

Regarding robot architecture, it begins with sensors, which are devices that capture information from the environment. The captured data from sensors are sent to a processing unit located on the robot. The control system interprets the processed data and determines the actions the robot can take. It involves algorithms for navigation, obstacle avoidance, and task execution. Actuators are responsible for carrying out the actions determined by the control system. The user interface serves as the bridge between humans and the computing system controlling robots. The computing system is responsible for processing user inputs received through the interface and generating appropriate commands for the robot to enable effective human–robot interaction [32].

2.6. Industry 5.0

The vision for Industry 5.0 shifts from a traditional, technology-driven focus on economic growth to a more transformative view of growth centered on human progress and well-being. Industry 5.0 complements and extends the hallmark features of Industry 4.0, by making production respect the boundaries of our planet and placing the wellbeing of the industrial worker at the center of the production process [2].

The overarching purpose of Industry 5.0 comprises three fundamental components: human-centricity, sustainability, and resilience [2].

A human-centric approach in industry puts core human needs and interests at the heart of the production process. Rather than asking the industry worker to adapt his or her skills to the needs of rapidly evolving technology, it is proposed to use technology to adapt the production process to the needs of the worker. It also means making sure the use of new technologies does not impinge on workers' fundamental rights, such as the right to privacy, autonomy and human dignity [2].

The term Sustainability has its foundations in the concept of "sustainable development" formulated in 1987 in the report "Our Common Future" produced by the United Nations World Commission on Environment and Development, in which it is mentioned that sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are carried out in a consistent manner, taking into account the needs of present and future generations. As a result of the aforementioned theoretical concept of "sustainability" of political origin, it surges the business approach theory of the "Triple Bottom Line" presented by John Elkington in 1997, in his work "Cannibals with forks", in which the author puts forward for the first time the idea that for a company to be sustainable it must guarantee a triple result: to be economically viable, to be socially beneficial and to be environmentally responsible [33].

The term resilience refers to the need to develop a higher degree of robustness in industrial production, arming it better against disruptions and making sure it can provide and support critical infrastructure in times of crisis [2].

2.7. Conceptual framework

Based on the previous definitions of the main theoretical concepts used in this work, a conceptual framework is presented in **Figure 1** to understand how the application of HFE contributes to the design and management of manufacturing HRC workstations to meet industry 5.0 objectives.

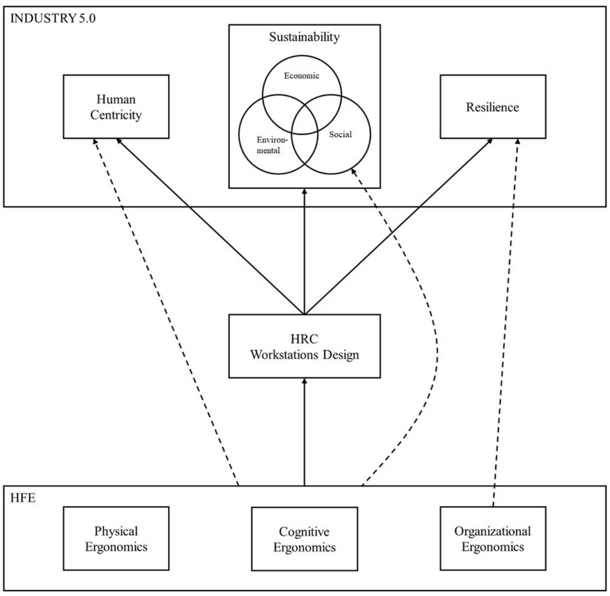

Figure 1. Conceptual framework.

3. Methodology

In this study, a Systematic Literature Review will be conducted to explore the scope of the existing academic debate on the application of HFE in the design and management of HRC workstations in the manufacturing industry adopting the industry 5.0 approach.

A systematic literature review is an organized, transparent and replicable research methodology for analyzing existing literature [34–37]. Previous studies have outlined several reasons for conducting a systematic literature review, such as synthesizing knowledge and determining gaps within existing research in a field, proposing areas for further research, and identifying current lines of research and potential future research topics [36].

The methodological phases to be applied will be based on [36,37]. The first phase involves planning the review process, which encompasses defining the research objectives and developing the review protocol. In this phase, categories will be formed according to the research questions posed. The second phase is conducting the review process, which involves the identification, selection, evaluation, and synthesis of relevant research studies. In this phase, the databases to be used, the inclusion and exclusion criteria, and the keywords to be used for the search will be determined. The third phase is reporting and dissemination of the overall research results, which consists of the descriptive reporting of the research findings and the presentation of their discussion and conclusions. In this study, this phase will be presented in sections 4 and 5.

3.1. Planning the review process phase

To achieve the objective of this study, the research questions must be answered. Therefore, in order to answer the research questions posed, the following categories have been created in this phase (See **Table 1**):

Table 1. Categories.

Research question	Category
RQ1	Literary production
RQ2	Context
RQ3	Main research topics addressed in HRC systems scientific literature

3.2. Conducting the review process phase

We limited the search to the period from 2020 to 2024. To select the articles, we used the following criteria for inclusion: We searched for appropriate articles that (a) mentioned the words: "Human Factors/Ergonomics", "Collaborative Robotics", "Industry 5.0", "Manufacturing", and "Collaborative Robotic Workstations Design" ; in the title, abstract or keywords; (b) reported theoretical and empirical investigations; (c) assessed antecedents, correlates, and consequences of the application of HFE in the design and management of Industrial HRC Workstations; (d) were published in peer-reviewed journals, and (e) were written in English.

The databases Scopus and Google Scholar were utilized in the search for articles. The search string was: (Ergonomics or Human Factors) and (Industrial Collaborative Robotics or Cobots) and (Industry 5.0) and (Manufacturing) and (Collaborative Robotic Workstations Design).

The search resulted in 465 potentially eligible articles, of which 254 were duplicates, and 128 were excluded based on the review of the titles and abstracts. Additionally, 29 studies were excluded after not being available in full-text and 14 after reviewing the full-text, leaving 40 articles available for the present study.

The PRISMA flowchart [38], which summarizes the abovementioned systematic review, is presented in **Figure 2**.

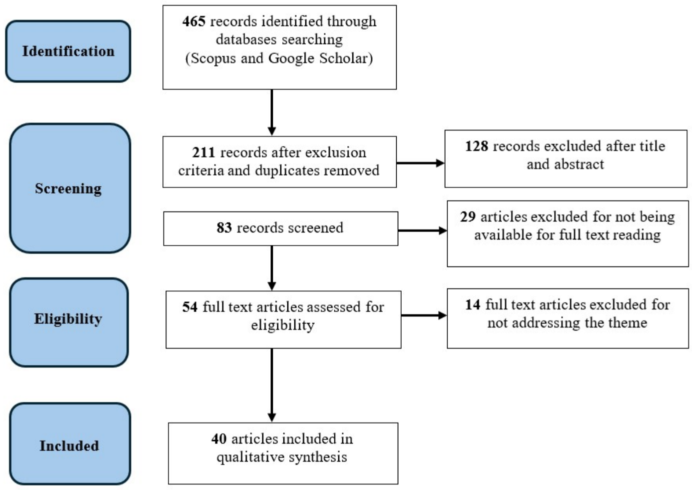

Figure 2. PRISMA protocol diagram for the systematic literature review performed.

4. Results

To facilitate the analysis of the findings of this research, a summary of the most relevant information from each of the forty articles under review is presented in **Table 2**.

Table 2. List of articles reviewed.

N	Ref.	Title	Journal	Year	Authors	Research type	Country	Industrial sector	Summary
1	[10]	A scoping review of Human Robot Interaction research towards Industry 5.0 human-centric workplaces	International Journal of Production Research	2024	Sotirios Panagou, W. Patrick Neumann and Fabio Fruggiero	Literature Review	Italy	Not specified	The aim of this work is to examine how robot design features affect operators at work to provide assistance to Human Robot Interaction (HRI) designers and practitioners.
2	[39]	A conceptual model for the acceptance of collaborative robots in industry 5.0	Procedia Computer Science	2022	Grandys Frieska Prassida and Ully Asfari	Conceptual Article	Indonesia	Not specified	This study provides a holistic view of the acceptance of collaborative robots (cobots) in the manufacturing context by adopting the socio-technical perspective to the Industry 5.0 era.
3	[40]	Factors influencing the intention of managers to adopt collaborative robots (cobots) in manufacturing organizations	Journal of Engineering and Technology Management	2020	Ana Correia Simões, António Lucas Soares, and Ana Cristina Barros	Exploratory research	Portugal	Automotive, packaging and security systems	This study identified and characterized the factors influencing managers' intentions to adopt collaborative robots (cobots) in manufacturing companies.
4	[41]	Value-Oriented and Ethical Technology Engineering in Industry 5.0: A Human-Centric Perspective for the Design of the Factory of the Future	Applied Sciences	2020	Francesco Longo, Antonio Padovano, and Steven Umbrello	Exploratory research	Italy	Not specified	This study addresses the ethical aspect in the design of cyber-physical production systems.

Table 2. (*Continued*).

N	Ref.	Title	Journal	Year	Authors	Research type	Country	Industrial sector	Summary
5	[42]	Research on the acceptance of collaborative robots for the industry 5.0 era -- The mediating effect of perceived competence and the moderating effect of robot use self-efficacy	International Journal of Industrial Ergonomics	2023	Shilong Liao, Long Lin, and Qin Chen	Experimental study	China	Not specified	This article analyzes the reasons for the low level of acceptance of workers to work with cobots in the workplace.
6	[43]	Multi-objective task allocation for collaborative robot systems with an Industry 5.0 human-centered perspective	The International Journal of Advanced Manufacturing Technology	2023	Martina Calzavara,Maurizio Faccio, and Irene Granata	Case study	Italy	Not specified	This study proposes a model for optimal task allocation that improves the performance of the HRI systems, both for efficiency and for workers' well-being.
7	[30]	Exploring the synergies between collaborative robotics, digital twins, augmentation, and industry 5.0 for smart manufacturing: A state-of-the-art review	Robotics and Computer-Integrated Manufacturing	2024	Muhammad Hamza Zafar, Even Falkenberg Langås, and Filippo Sanfilippo	Literature review	Norway	Not specified	In this study, a systematic review of the state of the art is presented to explore the synergies between cobots, DTs, augmentation, and Industry 5.0 for smart manufacturing.
8	[44]	Industry 5.0: prioritizing human comfort and productivity through collaborative robots and dynamic task allocation	Procedia Computer Science	2024	Irene Granata, Mauricio Faccio, and Giovanni Boschetti	Case study	Italy	Not specified	This study analyzes how the integration of cobots and human operators can affect performance and highlights the importance of taking human factors into account.
9	[45]	The Future of the Human–Machine Interface (HMI) in Society 5.0	Future Internet	2023	Mourtzis, D.; Angelopoulos, J.; and Panopoulos, N.	Review	Greece	Not specified	The aim of this paper is to identify the capabilities and distinguishing characteristics of both humans and machines, laying the groundwork for improving human–machine interaction (HMI).
10	[9]	Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review	Robotics and Computer Integrated Manufacturing	2021	Luca Gualtieri, Erwin Rauch, and Renato Vidoni	Sist. Literature Review	Italy	Not specified	The aim of this paper is to assess the state of the art for the design of safe and ergonomic collaborative robotic work cells.
11	[46]	Wire Harness Assembly Process Supported by a Collaborative Robot: A Case Study Focus on Ergonomics	Robotics	2022	Gabriel E. Navas-Reascos, David Romero , Ciro A. Rodriguez , Federico Guedea and Johan Stahre	Case study	Mexico	Plastics (wire harnesses)	This paper presents an early prototype and simulation to integrate a cobot into a wire harness assembly process, primarily for work ergonomic improvements.
12	[3]	Design of Human-Centered Collaborative Assembly Workstations for the Improvement of Operators' Physical Ergonomics and Production efficiency: A Case Study	Sustainability	2020	Luca Gualtieri, Ilaria Palomba , Fabio Antonio Merati, Erwin Rauch and Renato Vidoni	Case study	Italy	Plastics (wire harnesses)	The purpose of this work is to present a case study research for the design of a collaborative workstation to improve the operators' physical ergonomics while keeping or increasing the level of productivity.

Table 2. (*Continued*).

N	Ref.	Title	Journal	Year	Authors	Research type	Country	Industrial sector	Summary
13	[7]	Ergonomics and Human Factors as a Requirement to Implement Safer Collaborative Robotic Workstations: A Literature Review	Safety	2021	André Cardoso, Ana Colim, Estela Bicho, Ana Cristina Braga, Marino Menozzi and Pedro Arezes	Literature Review	Portugal	Not specified	In this article, the authors are interested in understanding the existing studies focused on Cobots' implementation with ergonomic requirements, and the methods applied to design safer collaborative workstations.
14	[8]	Multimodal Assessment of Cognitive Workload Using Neural, Subjective and Behavioural Measures in Smart Factory Settings	Sensors	2023	Zohreh Zakeri, Arshia Arif, Ahmet Omurtag, Philip Breedon and Azfar Khalid	Experimental study	UK	Not specified	In this study, factory workers' mental workload was assessed using physiological, behavioral, and subjective measures. The effect of task complexity, cobot movement speed, and cobot payload capacity on the mental stress of a human worker were observed for a task designed in the context of a smart factory.
15	[22]	Development of a Neuroergonomic Assessment for the Evaluation of Mental Workload in an Industrial Human–Robot Interaction Assembly Task: A Comparative Case Study	Machines	2023	Carlo Caiazzo, Marija Savkovic, Milos Pusica, Djordje Milojevic, Maria Chiara Leva and Marko Djapan	Case study	Serbia	Not specified	This study shows the development of a combinative assessment for the evaluation of mental workload in a comparative analysis of two assembly task scenarios, without and with robot interaction.
16	[47]	Smart and Sustainable Human-Centred Workstations for Operators with Disability in the Age of Industry 5.0: A Systematic Review	Sustainability	2023	Amberlynn Bonello , Emmanuel Francalanza and Paul Refalo	Literature Review	Malta	Not specified	The aim of this research work was to analyze literature's current state of the art on the design of workstations for operators with disabilities within the context of Industry 5.0.
17	[48]	Is Industry 5.0 a Human-Centred Approach? A Systematic Review	Processes	2023	Joel Alves, Tânia M. Lima and Pedro D. Gaspar	Literature Review	Portugal	Not specified	This research's main purpose and distinguishing point are to determine whether Industry 5.0 is truly human-oriented and how human centricity can be created with Industry 5.0 technologies.
18	[49]	Human Factors Considerations for Quantifiable Human States in Physical Human–Robot Interaction: A Literature Review	Sensors	2023	Nourhan Abdulazeem and Yue Hu	Literature Review	Canada	Not specified	The objective of this paper is to conduct an unbiased review encompassing the studies on human factors studied in research involving physical interactions and strong manipulation capabilities.
19	[13]	Ergonomic human-robot collaboration in industry: A review	Frontiers In Robotics and AI	2023	Marta Lorenzini, Marta Lagomarsino, Luca Fortini, Soheil Gholami, and Arash Ajoudani	Literature Review	Italy	Not specified	In this review article, the authors provide an overview of the existing ergonomics assessment tools as well as the available monitoring technologies to drive and adapt a collaborative robot's behavior.
20	[50]	Human-Robot Collaboration: Optimizing Stress and Productivity Based on Game Theory	IEEE Robotics and Automation Letters	2021	Costanza Messeri , Gabriele Masotti , Andrea Maria Zanchettin , and Paolo Rocco	Experimental study	Italy	Not specified	In this work, the authors propose a novel control strategy that exploits a game theoretic approach to model and locally estimate the state of collaboration in terms of human productivity and stress. Based on this estimate, a learning automaton suitably adjusts the production pace of the robot, thus influencing the dynamics of the cooperation.

Table 2. (*Continued*).

N	Ref.	Title	Journal	Year	Authors	Research type	Country	Industrial sector	Summary
21	[51]	A Unified Architecture for Physical and Ergonomic Human–Robot Collaboration	Robotica	2020	Federica Ferraguti, Renzo Villa, Chiara Talignani Landi, Andrea Maria Zanchettin, Paolo Rocco and Cristian Secchi	Experimental study	Italy	Not specified	In this paper, the authors propose an architecture for an ergonomic human–robot co-manipulation of objects of various shapes and weights.
22	[52]	An Online Framework for Cognitive Load Assessment in Assembly Tasks	Robotics and Computer-Integrated Manufacturing	2022	Marta Lagomarsino, Marta Lorenzini, Elena De Momi and Arash Ajoudani	Experimental study	Italy	Not specified	This paper presents a novel method for online assessment of cognitive load in manufacturing, primarily assembly, by detecting patterns in human motion directly from the input images of a stereo camera.
23	[53]	An Online Multi-Index Approach to Human Ergonomics Assessment in the Workplace	IEEE Transactions on Human-Machine Systems	2021	Marta Lorenzini, Wansoo Kim, and Arash Ajoudani	Experimental study	Italy	Not specified	This paper introduces an online approach to monitor kinematic and dynamic quantities on the workers, providing on the spot an estimate of the physical load required in their daily jobs.
24	[54]	Ergonomic design of Human-Robot collaborative workstation in the Era of Industry 5.0	Computers & Industrial Engineering	2024	Ali Keshvarparast, Nicola Berti, Saahil Chand, Mattia Guidolin, Yuqian Lu, Olga Battaia, Xun Xu, and Daria Battini	Experimental study	Italy	Not specified	This research proposes a new mathematical model to accelerate the design of ergonomic human-robot collaborative workstations based on task alternatives and the combined consideration of postural assessment and fatigue analyses for each of them.
25	[55]	A virtual reality-based ergonomic assessment approach for human-robot collaboration workstation design in modular construction manufacturing.	Advanced Engineering Informatics	2024	Yonglin Fu , Weisheng Lu, and Junjie Chen	Case study	China	Construction	This research introduces a novel approach for evaluating ergonomics using virtual reality (VR) during the HRC workstation design phase.
26	[56]	Towards Industry 5.0 - A Neuro ergonomic Workstation for Human-Centered Cobot-Supported Manual Assembly Process	IEEE Robotics and Automation Magazine	2024	Nikola Knežević, Andrej Savić, Zaviša Gordić, Arash Ajoudani, and Kosta Jovanović.	Experimental study	Serbia	Not specified	This paper brings the concept of neuro ergonomic work cell with its essential components for worker assessment (physical and psychological) and support (physical, non-physical and strategic) for improving the well-being and productivity of workers at their workplaces.
27	[57]	Achieving productivity and operator well-being: A dynamic task allocation strategy for collaborative assembly systems in Industry 5.0	The International Journal of Advanced Manufacturing Technology	2024	Martina Calzavara· Maurizio Faccio, Irene Granata, and Alberto Trevisani	Experimental study	Italy	Not specified	In this study, a dynamic real-time multi-objective task allocation strategy for collaborative assembly systems is developed in order to link the objectives of productivity, flexibility, and human factors consideration.
28	[58]	Updating design guidelines for cognitive ergonomics in human-centred collaborative robotics applications: An expert survey	Applied Ergonomics	2024	Luca Gualtieri, Federico Fraboni, Hannah Brendel, Luca Pietrantoni, Renato Vidoni, and Patrick Dallasega	Exploratory research	Italy	Not specified	This work aims to update, develop, and validate guidelines to assist non-experts in human factors and cognitive ergonomics in the early stages of the design of anthropocentric and collaborative assembly applications.

Table 2. (*Continued*).

N	Ref.	Title	Journal	Year	Authors	Research type	Country	Industrial sector	Summary
29	[59]	A novel human-centered methodology for assessing manual-to-collaborative safe conversion of workstations	Safety Science	2024	Andre Cardoso, Ana Colim, Estela Bicho, Ana Cristina Braga, and Pedro Arezes.	Case study	Portugal	Civil construction, cutlery, furniture, and automotive	This study introduces a novel methodology designed to assess the feasibility of converting manual tasks into collaborative ones.
30	[60]	Collaborative robots in manufacturing and assembly systems: literature review and future research agenda	Journal of Intelligent Manufacturing	2023	Ali Keshvarparast, Daria Battini, Olga Battaia, and Amir Pirayesh	Literature Review	Italy	Not specified	This research investigates the impacts of the integration of cobots in the context of assembly and disassembly lines. For this purpose, a Systematic Literature Review is performed.
31	[61]	Dynamic muscle fatigue assessment using s-EMG technology towards human-centric human-robot collaboration	Journal of Manufacturing Systems	2023	Saahil Chand, Andrew McDaid, and Yuqian Lu	Experimental study	New Zealand	Not specified	In this study, the authors created a theory for quantifying localized muscular fatigue by just understanding the relative task load and the number of repetitive operations the operator conducted.
32	[62]	Integrating collaborative robots in manufacturing, logistics, and agriculture: Expert perspectives on technical, safety, and human factors.	Frontiers in Robotics and AI	2024	Luca Pietrantoni, Marco Favilla, Federico Fraboni, Elvis Mazzoni, Sofia Morandini, Martina Benvenuti and Marco De Angelis	Case study	Italy	Vehicle assembly, warehouse logistics, and agricultural operations.	This study investigates the implementation of collaborative robots across three distinct industrial sectors: vehicle assembly, warehouse logistics, and agricultural operations.
33	[63]	Outlook on human-centric manufacturing towards Industry 5.0	Journal of Manufacturing Systems	2022	Yuqian Lu, Hao Zheng, Saahil Chand, Wanqing Xia, Zengkun Liu, Xun Xu, Lihui Wang, Zhaojun Qin, and Jinsong Bao	Conceptual Article	China	Not specified	This position paper presents the authors' arguments on the concept, needs, reference model, enabling technologies and system frameworks of human-centric manufacturing, providing a relatable vision and research agenda for future work in human-centric manufacturing systems.
34	[64]	A Comprehensive Study of Human Factors, Sensory Principles, and Commercial Solutions for Future Human-Centered Working Operations in Industry 5.0	IEEE Access	2023	Erlantz Loizaga, Aitor Toichoa Eyam, Leire Bastida, and José L. Martínez Lastra	Conceptual Article	Spain	Not specified	The purpose of this study is to explore the measurement of human factors in the workplace that can provide critical insights into workers' well-being. This paper provides an overview of these human factors and their specific influence on psycho-physiological responses, along with suitable technologies to measure them in working environments and the currently available commercial solutions to do so.
35	[65]	Emotion-Driven Analysis and Control of Human-Robot Interactions in Collaborative Applications	Sensors	2021	Aitor Toichoa Eyam , Wael M. Mohammed and Jose L. Martinez Lastra	Experimental study	Finland	Not specified	This paper presents an approach for adapting cobot parameters to the emotional state of the human worker.
36	[66]	A framework for human–robot collaboration enhanced by preference learning and ergonomics.	Robotics and Computer-Integrated Manufacturing	2024	Matteo Meregalli Falerni, Vincenzo Pomponi, Hamid Reza Karimi, Matteo Lavit Nicora, Le Anh Dao, Matteo Malosio, and Loris Roveda	Experimental study	Italy	Not specified	This paper addresses the need for a human-centered framework proposing a preference-based optimization algorithm in a human–robot collaboration (HRC) scenario with an ergonomics assessment to improve working conditions.

Table 2. (*Continued*).

N	Ref.	Title	Journal	Year	Authors	Research type	Country	Industrial sector	Summary
37	[67]	Sustainability of Human-Robot cooperative configurations: Findings from a case study.	Computers & Industrial Engineering	2023	Marta Rinaldi, Mario Caterino, and Marcello Fera	Case study	Italy	Aerospace	This paper proposes an empirical investigation for evaluating the sustainability of different degrees of Human-Robot cooperation (HRC) considering economic, environmental, and social pillars.
38	[68]	Assessing the Relationship between Cognitive Workload, Workstation Design, User Acceptance and Trust in Collaborative Robots	Applied Sciences	2023	Tommaso Panchetti, Luca Pietrantoni, Gabriele Puzzo, Luca Gualtieri and Federico Fraboni	Experimental study	Italy	Not specified	This study assessed the relationship between cognitive workload, workstation design, user acceptance and trust in collaborative robots, combining subjective and objective data to evaluate the cognitive workload during an assembly task in three different scenarios.
39	[69]	Digital and Virtual Technologies for Work-Related Biomechanical Risk Assessment: A Scoping Review	Safety	2024	Paulo C. Anacleto Filho, Ana Colim, Cristiano Jesus, Sérgio Ivan Lopes and Paula Carneiro	Literature review	Portugal	Not specified	This research centers on physical ergonomics, focusing on work-related biomechanical risk assessment. This study presents a comprehensive review of 24 commercial tools and 10 academic studies focusing on work-related biomechanical risk assessment using digital and virtual technologies.
40	[32]	Cobotics: The Evolving Roles and Prospects of Next-Generation Collaborative Robots in Industry 5.0	Journal of Robotics	2024	Md. Mijanur Rahman, Fatema Khatun, Ismat Jahan, Ramprosad Devnath, and Md. Al-Amin Bhuiyan	Literature review	Bangladesh	Automotive, construction, warehouse logistics, agricultural operations	The research presents real-world examples of successful Cobot integration across various industries, demonstrating benefits such as increased productivity, improved quality, and enhanced worker safety. Additionally, this study identified gaps in existing knowledge and contributions to the field.

Using the information provided in **Table 2**, the research findings are presented below according to the categories created to answer the research questions posed.

4.1. Literary production

4.1.1. Year of publication of reviewed articles

Of the forty articles reviewed, twenty-eight (70%) were published in the last two years of the review period (See **Figure 3**).

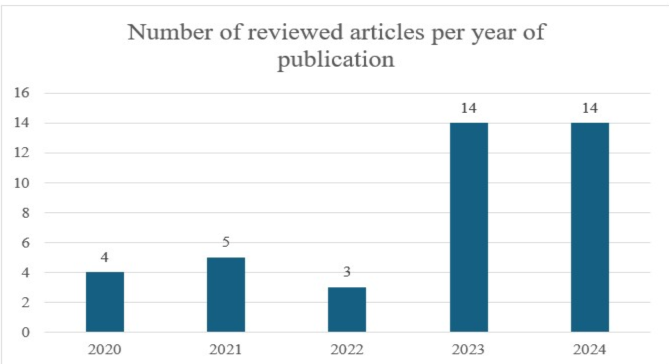

Figure 3. Number of reviewed articles per year of publication.

4.1.2. Research type

As for the type of research, the findings show that experimental studies (simulations in Laboratory), and literature reviews top the list with 32.5% and 30% respectively. Case studies are in third place with 22.5% (See **Figure 4**)

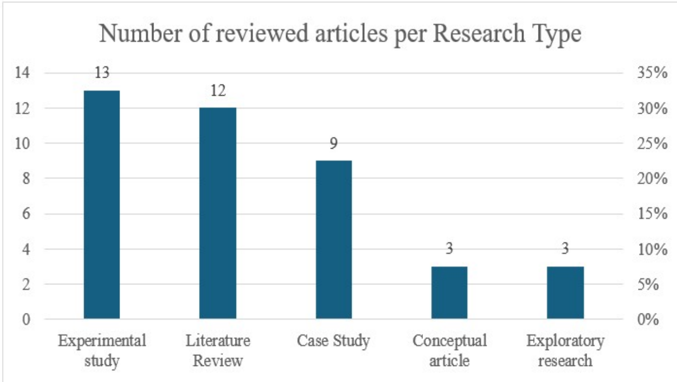

Figure 4. Number of reviewed articles per research type.

4.2. Context

4.2.1. Countries/continents where studies were conducted

The findings indicate that the country where the largest number of studies on the subject of this research were carried out was Italy. In terms of ranking by continent, Europe tops the list followed by Asia, with 80% and 12.5% respectively (See **Figures 5 and 6**).

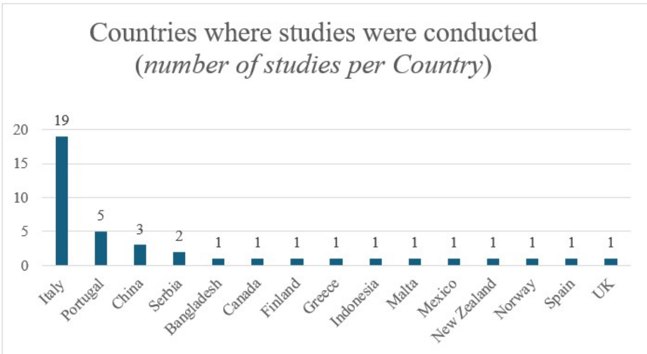

Figure 5. Countries where studies were conducted.

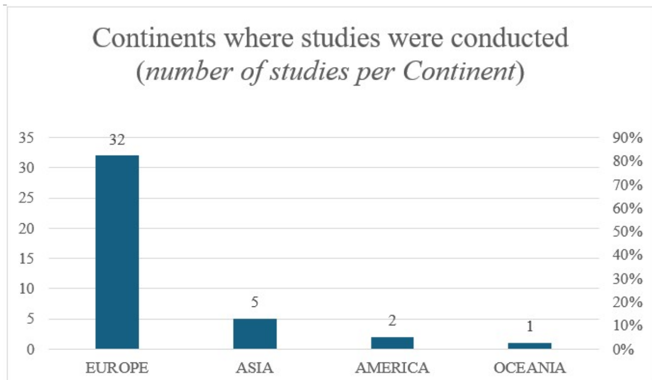

Figure 6. Continents where studies were conducted.

4.2.2. Industrial sector

Of the forty articles reviewed, only eighteen specified the industrial sector where the study was conducted. Of these, the findings show that the industrial sector in which most studies have been carried out on the subject of this research is the automotive sector (See **Figure 7**).

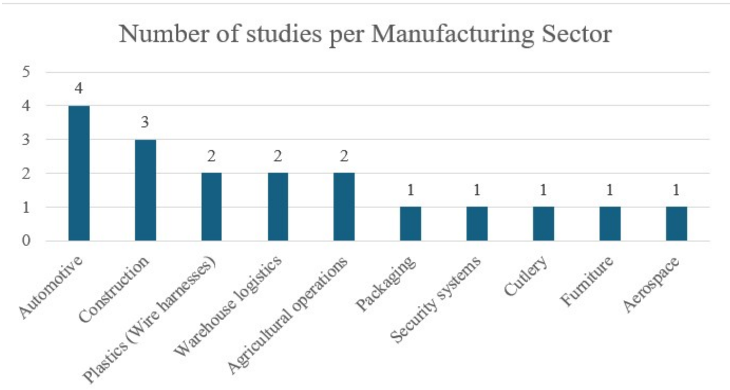

Figure 7. Number of studies per manufacturing sector.

4.3. Main research topics addressed in HRC systems scientific literature

According to the analysis of the articles presented in **Table 2**, it was found that the main research topics addressed in the scientific literature of HRC systems are as follows:

- Factors influencing the acceptance of cobots by human coworkers in the manufacturing context.
- Factors influencing managers' intentions to adopt cobots in manufacturing companies.
- Methodologies and tools used for ergonomics assessment in the context of HRC systems research.
- Task allocation strategies in HRC systems.
- Technical and ethical guidelines for the design of collaborative human-centered workstations.
- Assessment of Sustainability in HRC configurations.

The findings of the literature review conducted for each of the above topics are shown below.

4.3.1. Factors influencing the acceptance of cobots by human coworkers in the manufacturing context

It was found that robot appearance, robot capabilities and robot behavior changes are the most important factors that influence the acceptance of cobots by human coworkers in collaborative workplaces [10,42,62]. The effects on the human aspects of workers caused by the technical aspects of robots are shown in **Table 3**.

4.3.2. Factors influencing managers' intentions to adopt cobots in manufacturing companies

According to the Unified Theory of Acceptance and Use of Technology (UTAUT), there are four key dimensions that influence the behavioral intention of using cobots at the organization level: performance expectancy, effort expectancy, social influence, and facilitating conditions [39]. Additionally, according to a conceptual framework that integrates three technology adoption theories: Diffusion of Innovation, Technology-organization environment and Institutional theory; and following an exploratory qualitative research design, thirty-nine factors were identified as influencing managers' intention to adopt cobots in three contexts: internal context, external context and technological context. In the internal context, they are structural factors (size, age, top management support and attitude towards technology, and lack of resources); receptive internal context for change (associated with the ability to support new ideas and embrace change); and organizational readiness, including technological readiness. In the external context, the main factors are competitive pressure; business partner pressure; government/political directives (local and national); and the regulatory environment. In the technological context, the main factors are relative advantages; compatibility; complexity; portability of the knowledge required to use the technology; and support and augmentation (including customization, training, and help desk services) [40].

Table 3. Effects on the human aspects of workers caused by the technical aspects of robots.

Technical features	Human features
Robot appearance (anthropomorphism)	Perceived competence and perceived threat
Capabilities	Operators' perception and expectations concerning reliability and safety
Robot behavior changes	Human safety perceptions

Regarding the performance expectancy dimension, five performance criteria have been used in the literature: safety, cost, flexibility, productivity, and ergonomics. Findings revealed that productivity was the most used performance criterion, while flexibility was the least used due to the challenges in evaluating it [60].

4.3.3. Methodologies and tools used for ergonomics assessment in the context of HRC systems research.

As mentioned in section 2, there are three methodologies for performing both physical and cognitive ergonomic assessments: Subjective judgements, Systematic observations and Direct measurements. In that sense, the findings of the research conducted are shown below.

Most used methodologies and tools for physical ergonomics assessment in HRC systems.

Regarding the methodologies used for physical ergonomic assessment in HRC systems, it was found that Systematic Observations were the most used [3,7,13,46,51,53–55,59,61,64,66,69], followed by Direct Measurements [13,53,61,64], and lastly Subjective judgements [13] (See **Figure 8**).

Regarding tools for measuring physical ergonomics by Systematic Observations, the most widely used are the Rapid Upper Limb Assessment (RULA) [3,7,13,46,51,53,55,69], and the Rapid Entire Body Assessment (REBA) [7,13,53–55,69]. Both tools are used for posture and movement analysis (See **Figure 9**)

Regarding tools for measuring physical ergonomics by Direct Measurements, the most used are the Surface Electromyography (sEMG), [53,61,64], and the Electromyography (EMG) [13,64] (See **Figure 10**).

Regarding tools for measuring physical ergonomics by Subjective Judgements, the most widely used is the NASA-Task Load Index (NASA-TLX) questionnaire [13].

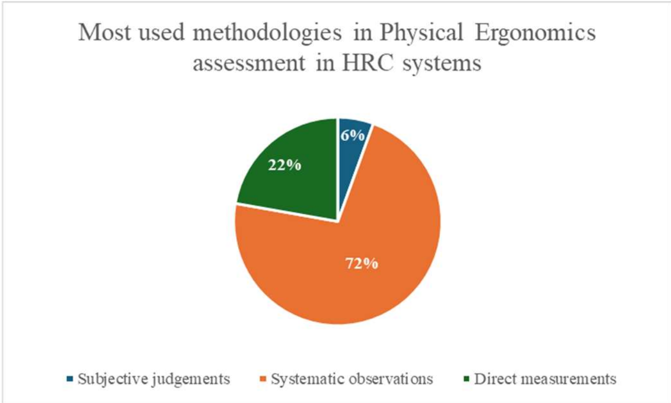

Figure 8. Most used methodologies in physical ergonomics assessment.

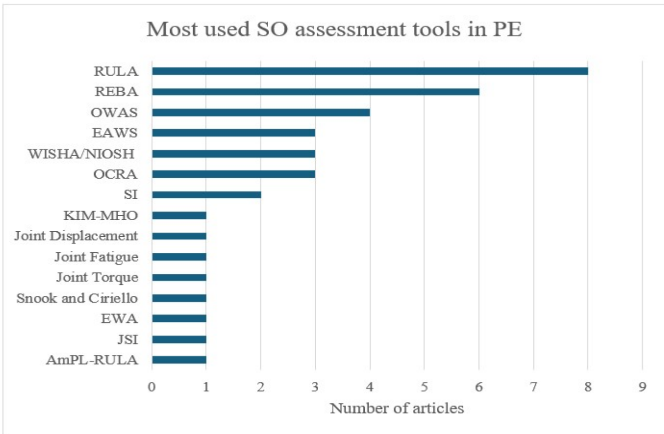

Figure 9. Most used Systematic Observations assessment tools in physical ergonomics.

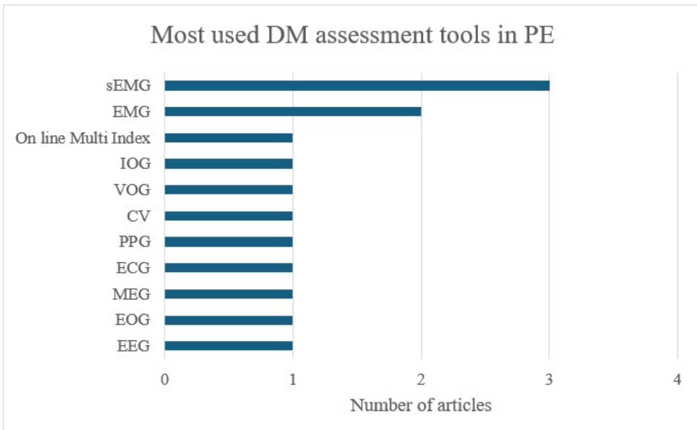

Figure 10. Most used Direct Measurements assessment tools in physical ergonomics.

Most used methodologies and tools for Cognitive Ergonomics assessment in HRC systems

Regarding the most commonly used methodologies for cognitive ergonomic assessment in HRC systems, it was found that Subjective Judgments were the most used [7,8,13,22,55,56,59,68], followed by Direct Measurements [8,13,22,50,56,64,65], and lastly Systematic Observations [8,13,52] (See **Figure 11**).

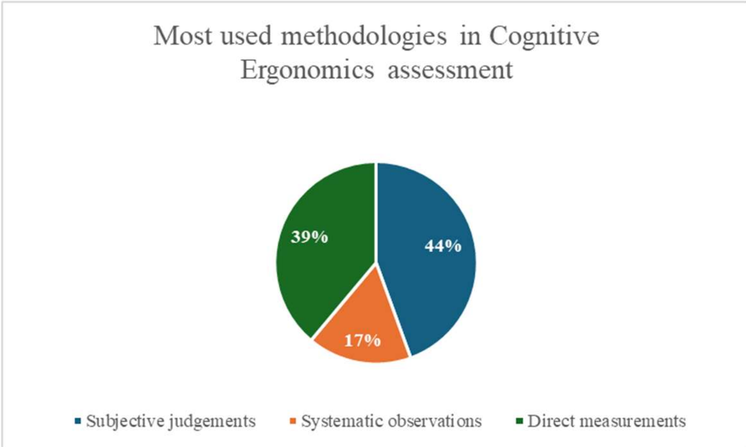

Figure 11. Most used methodologies in cognitive ergonomics assessment.

Regarding tools for measuring cognitive ergonomics by Direct Measurements, the most extensively used is the Electroencephalogram (EEG) [8,13,22,56,64,65] (See **Figure 12**).

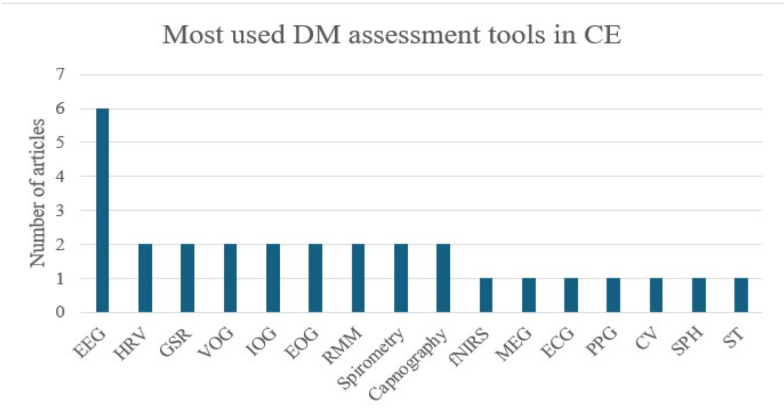

Figure 12. Most used Direct Measurement assessment tools in cognitive ergonomics.

Regarding tools for measuring cognitive ergonomics by Subjective Judgements, the most widely used is the NASA-Task Load Index (NASA-TLX) questionnaire [7,8,13,22,55,56,68] (See **Figure 13**).

Regarding tools for measuring cognitive ergonomics by Systematic Observations, the most used are the Visual Monitoring Systems (VMS) used for vision-based cognitive load assessments [13,52], and the Reaction Time and missed beeps (RTMB), used for behavioral measures [8].

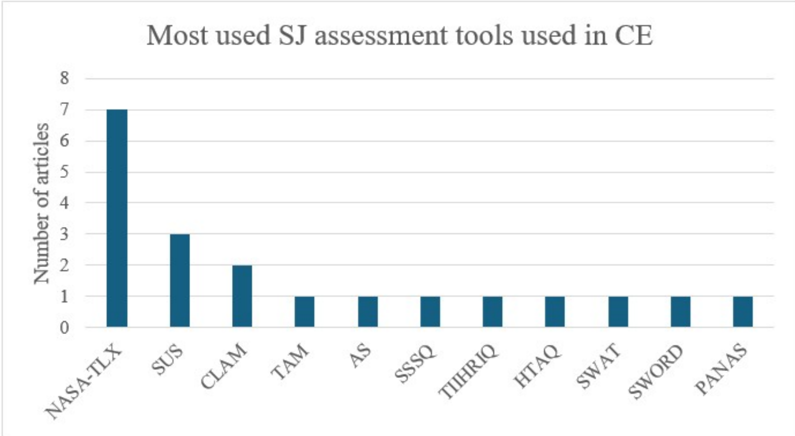

Figure 13. Most used Subjective Judgements assessment tools in cognitive ergonomics.

4.3.4. Task allocation strategies in human-robot collaboration systems

The findings of the literature review on task allocation strategies in human-robot collaborative systems showed that the focus is on proposing dynamic multi-objective task allocation methods to improve the performance of these systems, both in terms of efficiency (makespan) and worker welfare (operator's energy expenditure, and average mental workload) [43,44,57].

4.3.5. Technical and ethical guidelines for the design of collaborative human-centered workstations

The findings on this topic showed some technical and ethical guidelines to assist non-experts in the early stages of the design of anthropocentric and collaborative assembly applications.

Fifty-three technical guidelines have been proposed in [58], taking into consideration the main features that have positively influenced workers' cognitive responses. These guidelines are organized in five categories –Workstation and Robot System Features, Robot System Performance and Interaction Patterns, Human-Robot Communication and Interfaces, Control Measures, and Organizational Measures and Training– to better guide a designer through specific parts of the collaborative application.

Additionally, [41] suggested actionable steps that engineers and designers can take in their projects to address the ethical aspect in the design of cyber-physical production systems. The Value Sensitive Design (VSD) approach is proposed as a principled framework to illustrate how technologies enabling human–machine symbiosis in the Factory of the Future can be designed to embody elicited human values.

4.3.6. Assessment of Sustainability in HRC configurations

Of the forty articles reviewed, only one deals with this topic. In [67], the authors combined a Multiple-Criteria Decision-Making (MCDM) technique with case study-based research to assess the sustainability of an HRC assembly cell in the aerospace industry. Results demonstrate that the introduction of cooperation can offer economic benefits linked to productivity, efficiency and profitability. Positive effects on social sustainability have also been identified in terms of safety and physical ergonomics.

However, the presence of the robot could cause work-related stress and decrease the level of mental well-being. Additionally, authors mentioned that the introduction of HRC slightly affects environmental sustainability, increasing energy consumption, but decreasing waste due to manual errors.

5. Discussion

The fact that 70% of the articles reviewed were published in the last two years indicates that there is growing interest in the application of ergonomics in the design of human-robot collaborative systems using the Industry 5.0 approach and confirms that this is an emerging and not yet consolidated research topic.

As for the type of research, I believe that more research is needed on this topic through real case studies since the evaluation of HRC strategies with real workers in real factories is a key requirement.

In terms of the context in which the reviewed research was produced, Europe overwhelmingly leads the ranking. This is congruent with the fact that the European Union is leading the efforts toward the development of Industry 5.0.

Regarding factors that influence human employees' acceptance of cobots in manufacturing contexts, the reviewed studies conclude that cobots' anthropomorphism decreases their acceptance. The higher the degree of anthropomorphism in a cobot, the higher the level of competence that employees perceive. [42]. To counteract this, it can be useful to involve operators in the design and implementation phases of robots, train operators with robots before their implementation in the workplace or after a change in their features, and the use of advanced technology such as machine learning and AI in the robot design to support and protect operators, further improving actual and perceptual safety [10]. In addition, it is necessary to provide practical guidance for organizations implementing collaborative robotics that considers the use of comprehensive safety protocols tailored to each sector's unique requirements, the importance of user-friendly interfaces and intuitive programming methods for successful cobot integration, and the necessity of addressing workforce transition and skill development concerns [62].

Regarding factors influencing managers' intentions to adopt cobots in manufacturing companies, I believe that it is important to highlight the results obtained in [40] since that study was carried out by interviewing thirteen managers of six large European companies belonging to three major industrial sectors that have already adopted or are planning to adopt cobots. Furthermore, those managers had extensive knowledge and experience of the subject under study and were endowed with decision-making power in the definition and implementation of technological strategies. In this regard, the thirty-nine factors identified in the aforementioned study can help organizations in their process of adoption of cobots.

In terms of ergonomics assessment in HRC systems research, the findings showed that the most widely used methodology for assessing physical ergonomics is "Systematic Observation". The most used assessment tools for this methodology are RULA and REBA. Nevertheless, these tools must be employed by trained experts as an offline procedure after collecting observations/recordings, which is time consuming and does not provide immediate results. For this reason, the literature indicates that many assessment tools in this category have recently been automated and use sensor technologies and algorithms to conduct online ergonomics assessments and adjust the robot control strategy based on the worker's stress and needs [13]. In this context, the proposal of [66] of the AmPL–RULA framework within a HRC scenario is a noteworthy contribution. This tool combines an Active multi-Preference Learning (AmPL) algorithm, a preference-based optimization method, with the ergonomic performance index RULA, so that the optimal setting can be computed to improve working conditions.

The second most used methodology for measuring physical ergonomics is "Direct measurement". The use of sensors is an integral part of this methodology and facilitates online measurement. Direct measurements collected on the human subjects through suitable sensor systems are generally integrated with complex models of the human body. Several algorithms were proposed for estimating muscle tensions and joint loads using detailed models of the human musculoskeletal system [13]. The most used assessment tools for this methodology are surface electromyography (sEMG) and electromyography (EMG). These tools are used to adapt online robot behavior to human fatigue, which was modelled based on human muscle activity measured with EMG sensors.

Lastly, the least used methodology for evaluating physical ergonomics is "Subjective judgment". Furthermore, because this methodology is vulnerable to many influences several studies have shown that it has too low validity and reliability with respect to the demands for ergonomic interventions [13].

Regarding cognitive ergonomics assessment in HRC systems research, the findings showed that the most used assessing methodology is "Subjective judgment". The most used assessment tool for this methodology is the NASA-TLX questionnaire. Nevertheless, the main drawback in using this tool is the assumption that people can introspect in the cognitive processes and report accurately the amount of experienced cognitive effort. Furthermore, this tool works offline, and the deep comprehension of collected data requires specific skills in the field of cognitive ergonomics and cognitive science [13].

The second most used methodology for measuring cognitive ergonomics is "Direct measurement". This methodology through direct measurements of physiological signals provides objective and quantitative information and permits the visualization of continuous trends and the identification of detailed patterns of cognitive load. The most used assessment tool for this methodology is the Electroencephalogram (EEG). Nevertheless, it must be mentioned that motion artefacts and noise due to electrical interference, breathing and heartbeat make the EEG signal not deployable in industrial settings. For this reason, the adoption of the technology in real-world scenarios is subject to certain limitations [13].

Lastly, findings show that the least used methodology for evaluating cognitive ergonomics is "Systematic observation". This is mainly because it significantly interferes with normal task performance and is therefore rarely applicable, even in laboratory settings [13]. For this reason, the applicability of external sensory systems to visually monitor worker behavioral characteristics and changes has recently been investigated to design less obtrusive monitoring systems and to maximize user comfort [52].

Finally, in my opinion, regarding ergonomic assessment, it can be inferred that both the "Subjective Judgement" methodology and the "Systematic Observation" methodology, when applied offline, are more suitable for static work environments. However, in highly dynamic work environments, such as those found at HRC workstations, it is necessary to prioritize the use of the "Direct Measurement" methodology. This methodology is applied online to obtain the worker's physiological and cognitive responses in real time, which allows the robot's behavior to be adjusted to the worker's physiological and mental state. It should be mentioned that most of the reviewed studies that applied Direct Measurements were conducted in simulated environments rather than in real-world industrial settings, which do not guarantee reliable results. In that sense, I recommend that future research be conducted on the application of this methodology in real-world work environments. According to the literature reviewed, one of the main obstacles to applying this methodology in real industrial settings lies in the susceptibility of signal transmission from measuring devices to external factors inherent to the work environment, including noise from machinery and equipment. From an industrial engineering perspective, I suggest implementing a soundproofing system when designing HRC workstations. This would prevent signal distortion caused by ambient noise when the "Direct Measurement" methodology is applied.

Regarding task allocation strategies in human-robot collaboration systems, as previously mentioned, the findings show that the focus is on proposing dynamic multi-objective task allocation methods to improve the performance of these systems in terms of efficiency and worker welfare. In addition, it should be mentioned that unlike previous years where studies focused on taking into account only physical ergonomics to adapt the cobot routine to that of their human partner in order to reduce the worker's physical effort and reduce costs, the findings show that in the last two years, task allocation strategies in HRC systems have focused on taking into account cognitive ergonomics to reallocate tasks according to the needs of the operator to improve the performance of these systems.

Regarding technical and ethical guidelines for the design of collaborative human-centered workstations, I believe that the articles written by [41] and [58] should be highlighted. In the first study the technical guidelines have been proposed from the results of a systematic scientific literature review, whose preliminary validation has been carried out with the help of researchers working in the field. Additionally, a survey has been used to examine in depth how international experts in different branches can interpret such guidelines. In the second study, authors addressed the ethical aspect in the design of cyber-physical production systems, arguing that value-oriented and ethical technology engineering in Industry 5.0 is an urgent and sensitive topic as demonstrated by a survey administered to industry leaders from different companies. Using cases based on real solutions and prototypes, this study discusses how a design-for-values approach aids in the investigation and mitigation of ethical issues emerging from the implementation of technological solutions.

With respect to the evaluation of sustainability in HRC configurations, it is noteworthy that among the forty studies examined in this study, only a single study addresses the assessment of sustainability in the domain of human-robot collaborative manufacturing. In this sense, it is my belief that the subject of sustainability assessment in HRC systems remains an unconsolidated topic that necessitates further research.

6. Conclusions

The aim of this research was to explore the current state of the art regarding the application of HFE in the design and management of HRC workstations in the manufacturing industry adopting the Industry 5.0 approach.

A systematic literature review was conducted, and a total of forty scientific journal articles published in the last five years were identified that met the established inclusion criteria. Three categories were created to answer the research questions posed.

Based on the findings of this study it can be concluded that there is a growing interest, particularly in Europe, in applying HFE to the design of HRC manufacturing workstations under the Industry 5.0 framework. In addition, the findings indicated a significant shift in the focus of research towards the application of cognitive ergonomics in HRC manufacturing systems, which has superseded the study of the application of physical ergonomics in recent years. Furthermore, findings also revealed a growing reliance on Direct measurement methodologies, utilizing advanced sensors and algorithms to monitor workers' physiological responses in real time to inform adaptive cobot behavior. However, most of these studies were conducted in simulated environments rather than in real-world industrial settings.

Likewise, this study identified critical factors influencing cobot integration. Worker acceptance is primarily affected by robot appearance, capabilities, and behavioral patterns. Managerial intentions to adopt cobots are shaped by internal factors (e.g., organizational size, leadership attitudes, resource availability), external pressures (e.g., competitive landscape, regulatory directives), and technological considerations (e.g., compatibility, complexity). In terms of organizational ergonomics, recent research on task allocation in HRC systems emphasizes dynamic, multi-objective strategies to optimize both system efficiency and worker well-being. As for the technical and ethical guidelines for the design of HRC workstations, the technical guidelines for HRC design are grouped into five key areas: workstation and robot system features, system performance and interaction, communication interfaces, control measures, and organizational training. Ethical design considerations are addressed through the Value Sensitive Design (VSD) framework, promoting technological development aligned with human values. With regard to the evaluation of sustainability, the sustainability assessment of HRC systems remains largely underexplored, with only one of the forty reviewed articles addressing this aspect.

Finally, it can be concluded that the application of HFE contributes to the design and management of manufacturing HRC workstations to meet Industry 5.0 objectives, as was shown in **Figure 1**. However, many authors of the reviewed articles affirmed that the inclusion of ergonomic criteria in this area is far from widespread. In that sense, it is hoped from a practical point of view that the findings and conclusions of this study may be used by designers and practitioners to improve the design of HRC workstations by adopting the Industry 5.0 approach, prioritizing the inclusion and control of HFE to make manufacturing environments more human-centered, sustainable, and resilient.

From an academic perspective, it is hoped that this study will serve as an updated reference for future research, thereby facilitating the expansion of knowledge on the application of HFE in the design and management of HRC manufacturing environments, as a means of achieving the vision of Industry 5.0. Furthermore, it is hoped that this study will encourage more research on the subject from ergonomics specialists, particularly industrial engineers, given that many of the articles reviewed in this study were authored by robotics specialists.

6.1. Future directions and limitations

6.1.1. Future directions

According to the analysis of the articles presented in **Table 2**, it was found that the challenges and future research fields in HRC systems in Industry 5.0 focus on the adoption of novel technologies, such as artificial intelligence (AI), internet of things (IoT), robotics, extended reality (XR) or 'augmentation', cloud computing, 5G networks and digital twins (DTs), as an interface for the teaming aspiration of Industry 5.0 [30,45].

Findings also showed that future research on human–robot collaboration (HRC) systems need to orient its directions toward:

- Development of new metrics and tests for Cognitive ergonomics assessment [9].
- Design of workstations for operators with disabilities within the context of Industry 5.0 [47].
- Review and redesign of engineering education to train future engineers with technological, data, and knowledge fluency to make industries more resilient, sustainable, and human-centric in the era of Industry 5.0 [48].
- Direct and indirect physical assistance applications for older adults [49].
- Development of transparent, trustworthy and quantifiable technologies that provide a rewarding working environment driven by real-world needs taking account the Industrial Human Needs Pyramid [63].
- Integration of advanced AI algorithms, more sophisticated sensors, and improved human–robot interfaces to enhance cobots capabilities [32].
- The application of cutting-edge technologies like digital twin HRC (DT-HRC), which can enhance predictive modeling and real-time simulation of human-robot interactions, potentially leading to safer and more efficient collaborative environments. This technology facilitates ergonomic analysis providing real-time feedback concerning the human body's movements, thereby enabling the identification and rectification of any ergonomic concerns that may emerge during human-robot interactions [30].

Additionally, to the findings above mentioned, it is recommended that future research focus on studying the application of the "Direct measurement" methodology for evaluating physical and cognitive ergonomics through real case studies in industrial environments.

It is also recommended that future research on HRC systems focus on sustainability assessment to develop metrics that can objectively monitor the economic, environmental and social benefits of implementing HRC systems in manufacturing companies from an Industry 5.0 perspective. From an industrial engineering perspective, I recommend that the impact of applying HFE in the design of HRC workstations can be measured using the following sustainability metrics:

- In the economic aspect: Total productivity, Labor productivity, Total Operating cost.
- In the social aspect: Number of compensated occupational diseases, Percentage of total absence-hours on health and safety grounds, Percentage of hours of training regarding occupational health and safety, number of workers with disabilities, number of older workers, number of female workers.
- In the environmental aspect: Energy consumption, waste for recycling and disposal.

Furthermore, it is recommended that the list of indicators presented above be expanded in future studies, and that balanced scorecards be developed to effectively monitor the impact of applying HFE in the design of HRC workstations.

It is important to note that one of the proposed indicators for measuring the social aspect of sustainability is the number of employees with disabilities. This is significant because people with disabilities are generally not selected for operational roles in manufacturing environments. However, the workplace design should also be friendly with operators with disabilities. Technologies should enhance their human capacities, not excluding them to accomplish the concept of human-centricity. According to the reviewed literature, most studies have already been conducted on the implementation of technology to assist workers with physical disabilities (hearing, visual, and motor impairments) in their operational tasks. However, research on integrating workers with cognitive disabilities is still in its early stages. This would also be a future line of research in the context of HRC workstations, particularly for workers with psychological disorders that prevent collaborative work with robots.

Finally, regarding the context in which the reviewed research was developed, based on the findings, it is recommended further research on the topic under study in America, especially in Latin American countries where manual labor prevails in manufacturing factories.

6.1.2. Limitations

The main limitation of this study concerns the nonprobability nature of the sample consisting of forty articles. This research complies with the methodology recommended for systematic literature review; however, future research employing probability sampling methods could enhance the representativeness of the findings and allow for broader generalizations.

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Abbreviations

AS	Acceptance scale
CLAM	Cognitive load assessment for manufacturing
CV	Computer vision
EAWS	Ergonomic assessment worksheet
ECG	Electrocardiography
EEG	Electroencephalography
EMG	Electromyography
EOG	Electrooculography
EWA	Ergonomic workplace analysis
fNIRS	Functional near-infrared spectroscopy
GSR	Galvanic skin response
HRV	Heart rate variability
HTAQ	Human trust in automation questionnaire
IOG	Infrared oculography
JSI	Job strain index
KIM-MHO	Key Indicator Method for Manual Handling Operations
MEG	Magnetoencephalography
NASA-TLX	Nasa task load index
NIOSH	National Institute for Occupational Safety and Health, Lifting Equations
OCRA	Occupational Repetitive Actions
OWAS	Ovako Working Analysis System
PANAS	Positive and negative affect schedule
PPG	Photoplethysmography
REBA	Rapid Entire Body Assessment
RMM	Respiratory motion monitoring
RTMB	Reaction Time and missed beep
RULA	Rapid Upper Limb Assessment
sEMG	Surface electromyography
SI	Strain index
SPH	Secondary pulmonary hypertension
SSSQ	Short Stress Questionnaire
ST	Skin temperature
SUS	System usability scale
SWAT	Subjective workload assessment technique
SWORD	Subjective workload technique
TAM	Technology acceptance model
TIIHRIQ	Trust in Industrial Human–Robot Interaction questionnaire
VMS	Visual monitoring systems
VOG	Video-oculography
WISHA	Washington Industrial Safety and Health Act, Lifting calculator

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