Discover Mechanical Engineering

Review

Advances and perspectives in collaborative robotics: a review of key technologies and emerging trends

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Abstract
This review paper provides a literature survey of collaborative robots, or cobots, and their use in various industries. Cobots have gained popularity due to their ability to work with humans in a safe manner. The paper covers different aspects of cobots, including their design, control strategies, safety features, and human–robot interaction. The paper starts with a brief history and evolution of cobots, followed by a review of different control strategies and Safety features such as collision detection and avoidance, and safety-rated sensors are also examined. Further to this, a systematic review of Ergonomics is also taken into account. Additionally, the paper explores the challenges and opportunities presented by cobot's technology, including the need for standards and regulations, the impact on employment, and the potential benefits to industry. The latest research in human–robot interaction is also discussed. Finally, the paper highlights current limitations of cobot's technology and the need for further research to address technical and ethical challenges. This synthesis document is an invaluable resource for both academics and professionals interested while developing and application of cobot's technology.

Keywords Cobots · Collaborative robots · Human Robot Interaction (HRI) · Ergonomics · Collision avoidance · Contact detection

1 Introduction

Collaborative robots, commonly known as cobots, are transforming the way humans and robots collaborate in shared workspaces. The need for enhanced productivity and efficiency in industries, including manufacturing, logistics, and healthcare, has fuelled the development of cobots. Cobots are distinct from conventional industrial robots as they are intended to operate securely and efficiently in conjunction with human workers, providing greater flexibility and adaptability in the workplace.

One of the key challenges in developing collaborative robots is creating systems that can effectively perceive and respond to their environment. To address this challenge, researchers are exploring the utilization of computer vision and sensory modalities to boost the abilities of cobots in collaborative workspaces. Computer vision allows cobots to perceive their environment through visual data, while sensory modalities such as force-torque sensors and lidars provide additional feedback on the cobots' movements and interactions with their environment.

To gain a better context and appreciate the importance of collaborative robots, it is crucial to comprehend industrial robots. Industrial robots are programmable and autonomous machines comprising electronic, electrical, and mechanical components, capable of executing a complex set of operations. These robots are massive, inflexible, and are usually

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installed to perform dangerous and physically demanding tasks that may be hazardous for human, such as transporting heavy loads in factories. Generally, industrials robots are designed for specific applications, kept separate from human workers, and occupy a distinct workspace. In contrast, collaborative robots, also known as co-bots, are intended to operate alongside human workers in the same workspace. These robots weigh a lot less compared to traditional industrial robots, enabling greater mobility and ease of movement within the factory or workspace or industry that they are installed in. One of the advantages that cobots offer over industrial robots is their flexibility, as they can be used to perform multiple tasks, making them highly adaptable to changing work requirements.

This review's objective is to give sufficient information on the state of the art for HRI in artificial cobotic fields. A collaborative system is created to conduct business with a living being within a predetermined collaborative workspace where mechanical hazards are most likely to arise. This is because when humans and robots share a workplace, it is feasible for implicit, non-functional (and undesirable) linkages to form. While collaborative robots offer several crucial safety precautions that permit the execution of safe operations, this status typically changes as they are incorporated into a working environment and outfitted with various end-effectors kinds. Because of this, it's important to properly enforce safety rules regarding the design of the work cell as well as devices for preventing collisions and/or contact mitigation.

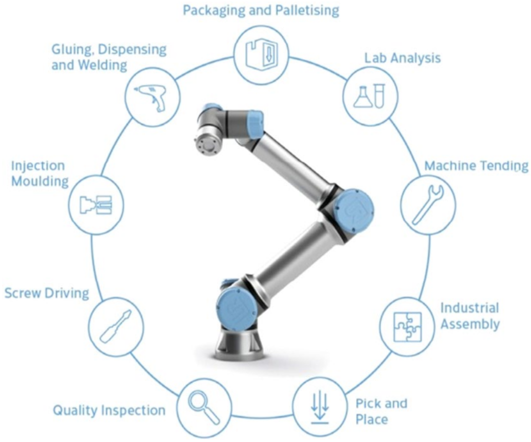
The psychophysical and social well-being of drivers is a part of ergonomics, often known as human factors. Physically speaking, collaborative robots can lighten the pressure on drivers by helping them with laborious and repetitive duties. As opposed to that, a close partnership can stress out drivers' brains. In fact, the unidentified robot movements may hurt drivers' abilities and performances.

Because of this, cognitive ergonomics in collaborative robots is a genuinely new and sometimes overlooked concept. Drivers may experience mental stress due to teamwork. In fact, the unidentified robot movements may hurt drivers' abilities and performances. Because of this, cognitive ergonomics in collaborative robots is a genuinely new and sometimes overlooked concept. So as to move collaborative robotics from the laboratory to the workshop or manufacturing facility of the industry, the purpose of this study is to examine the state-of-the-art in collaborative robotics safety and ergonomics and to pinpoint those research areas that are very significant (Fig. 1).

1.1 History of collaborative robots

The history of industrial revolutions sheds light on where collaborative robots stand in terms of industrial technological advancements. Industrial revolutions are defined as changes in technology used in manufacturing and production industries during a specific time period. The seventeenth century saw the beginning of the industrial revolution, saw the introduction of water and steam power to mechanize machines, which revolutionized manufacturing and allowed for mass production and assembly lines. The second industrial revolution, in the late eighteenth century added electricity to the equation and replaced steam engines with electrical ones. The third industrial revolution, in the late nineteenth century, saw the introduction of computers and automated machines, leading to further automation and increased manufacturing and assembly line capacities with increased productivity.

Fig. 1 Application of COBOTS



Industry 4.0, the latest and most advanced concept of industrial revolution, was coined in Germany in 2011. Industry 4.0 uses digitization and networked production, incorporating IoT, cyber-physical systems, and cloud computing to create "Smart Factories." Although the concept of collaborative robots predates Industry 4.0, they have become increasingly relevant to the production and manufacturing industry with the advent of this latest revolution. In shared workspaces, collaborative robots are made to function effectively and safely next to human workers. They are programmed to perform a range of tasks, such as assembly, welding, packaging, and inspection, among others. Cobots have a range of sensors on board and technologies that allow them to detect and avoid collisions with human workers and adjust their movements based on human input (Figs. 2, 3).

1.2 Difference between robots and cobots

See Table 1

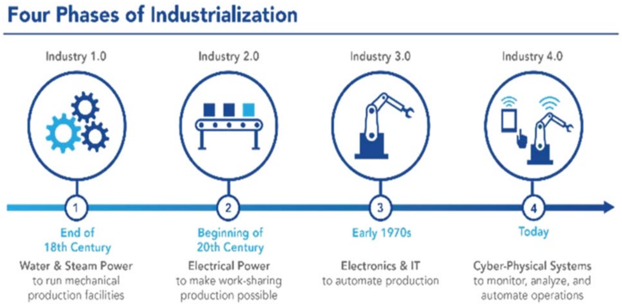


Fig. 2 History of COBOTS

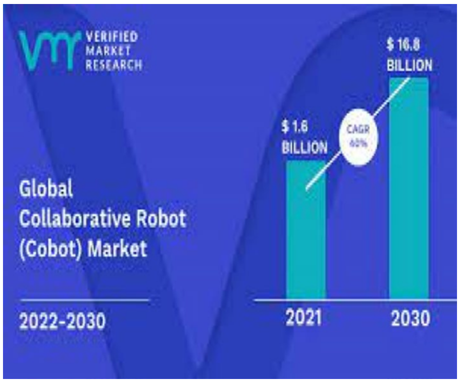


Fig. 3 Market of COBOT

Table 1 Difference between cobots and robots

	Conventional robot	Cobot
Purpose	Perform tasks automatically	Collaborate with humans
Programming	Typically pre-programmed or scripted	Easily programmed by humans
Safety	Require safety measures and barriers to protect humans	Designed to work alongside humans without endangering them
Flexibility	Designed to perform a specific group of tasks	Can perform a wide range of tasks
Cost	Typically expensive	Less expensive than conventional robots
Complexity	More complex to program and operate	Simple to program and operate
Payload	High payload capacity	Lower payload capacity
Accuracy	Lower precision	High precision
Size	Bulky and Space consuming	Smaller and dense
Application	Manufacturing and assembly lines	Small-scale manufacturing, research and development

1.3 Types of cobots

- *Independent*

Robots that can work independently and collaboratively with humans are created for different manufacturing processes and on different job items. So as to make sure that the cobots can operate securely and effectively without the need for cages or fences, this sort of collaboration often uses sensors and other safety elements. Robots that can work independently and collaboratively with humans are created for different manufacturing processes and on different job items.

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- *Simultaneous*

A human operator and a collaborative robot (cobot) work simultaneously on different production processes at the same work piece in simultaneous collaborative robots. There is no task or time dependency in this kind of collaboration between humans and cobots. Concurrently working on the same piece of work reduces transit time and boosts productivity and space efficiency.

By allowing cobot to carry out potentially hazardous duties for a human operator, simultaneous collaboration can also increase safety in dangerous circumstances.

- *Sequential*

Sequential collaborative robots are used to undertake successive production procedures on the same work item with a human operator. The operator’s operations and those of the cobots are time-dependent, with the cobot being tasked with handling more time-consuming or repetitive activities, which may also improve the operator’s working conditions.

This kind of cooperation is beneficial for boosting output, cutting down on errors, and cutting down on idle time in between activities. Working together sequentially is frequently employed in processes like assembly, welding, and material handling.

- *Supportive*

Supportive collaborative robots are a subset of collaborative robots that allow an operator and cobots to collaborate while working on the same task or piece of work. As one cannot complete the task without the other, there may be complete dependencies between the human and the cobots in this type of situation. Together, the cobot and human operator strive to accomplish a single objective, each balancing the other’s advantages and disadvantages.

Some common applications of supportive collaborative robots include assembly tasks, pick-and-place operations, and quality control inspection.

2 Literature survey

This section offers a survey of latest studies on interactions between human and robots in commercial collaboration robotics. Additionally, it suggests dividing the information in these works’ content into two groups: Safety and Ergonomics. The Safety category includes works focused on developing safe human–robot interaction systems and ensuring the safety of human workers in shared workspaces. The Ergonomics category includes works focused on improving the ergonomic design of collaborative robots to enhance the comfort and efficiency of human workers. Furthermore, this chapter addresses the challenges associated with industrial Cobots and identifies potential areas for future research.

One major challenge is the development of effective communication systems that enable seamless cooperation between machines and people. Additionally, there is a need for the development of advanced sensing technologies that enable robots to perceive and respond to their environment in real-time.

In conclusion, this chapter highlights the emergence of collaborative robots and the need for new human–robot interaction systems to fully utilize their capabilities. It also provides a classification of recent works in the field and addresses challenges and future research directions.

- Materials and methods

There are several papers and journals and hence to take the most relevant into account review should be carried out using systematic, scientific, and transparent and in reliable method.

To carry out scientific review on Collaborative Robotics we followed following steps for study:
Step 1: defining the study's or reviews scientific objectives;
Step 2: defining the explorations amorphous borders;
Step 3: setting the conditions for data collection;
Step 4: validation of result and classification.

1. *Defining the study's or reviews scientific objectives*

The following research questions allowed us to determine the study's goals:
RQ1. What are the main research themes or areas of research in collaborative robots?
RQ2. Classification of research themes and identifying the most prominent out of Safety and Ergonomics.
RQ3. What are the research gaps and research challenges?

In the most recent scientific literature, researchers have mostly focused on safety and ergonomics (or human aspects) for cobots intended for industrial usage. This review study will assist us in understanding and examining the most recent research issues and areas in safe and comfortable collaborative robotics. To use collaborative and participatory workplaces successfully in assiduity, we specifically want to comprehend how the exploratory results obtained in recent times can be dispersed and where we need to focus in the future.

2. *Defining the exploration's amorphous borders*

When reviewing literature on cobots, it is important to establish conceptual boundaries to ensure that the review is focused and relevant to the research question or topic at hand. Some possible conceptual boundaries to consider include:

- Type of collaboration: collaborative robots can interact with humans in a variety of ways viz Supportive, Sequential, Simultaneous or Independent. Researchers may choose to focus on a particular type of collaboration to better understand the specific issues related to that type of interaction.
- Safety and ergonomics: safety and ergonomics are critical considerations in the design and implementation of collaborative robots. Researchers may choose to focus specifically on these aspects of collaborative robot research understand the latest state of the art and identify areas for improvement.
- Technical approaches: collaborative robot research can involve a range of technical approaches, including control algorithms, sensing technologies, and human–robot interface design. By focusing on a specific technical approach, researchers can gain a deeper understanding of the strengths and limitations of that approach and identify areas for future research and development.
- Human factors: collaborative robots are designed to work alongside humans, and as such, understanding human factors is essential to their successful implementation. Researchers may choose to focus specifically on human factors research related to collaborative robots, such as user acceptance and trust workload and cognitive demands, and the impact of robot behavior on human performance.

These are just a few possible conceptual boundaries to consider when reviewing literature on collaborative robots.

3. *Setting the conditions for data collection*

We linked pertinent documents for our investigation in several ways.

As a preliminary step, we used the following search phrases for the title, abstract, and keywords to link the literature in the collaborative robotics field: Cobots, collaborative robots, human-robots, collaborative robotics, etc. All types of topics and documents were included in this initial step.

The terms "industry," "artificial," "manufacturing," "assembly," and "product" were included to the hunt terms in this alternative stage because we focused on collaborative robotics in the artificial sector as robotic results.

The following stage was to concentrate our investigation on pertinent engineering or computer science exploration studies.

The search was limited to using the journal as a source in order to solely examine high caliber content. To concentrate the research on problems related to the design of collaborative workplaces, we further limited the search to the topic categories "Engineering" and "Computer Science."

In the fourth step, we split the results of the hunt into two groups, one for a workshop discussing safety and the other group discussing ergonomics. As a result, we divided the data into two groups, one using the phrase "safety" and the other using "ergonomics" or "human factors".

4. *Validation of result and classification*

As per research questions, our prime objective are to segregate the state of the art literature of collaborative robotics into different clusters and sub clusters and identifying the most prominent cluster.

In this stage, initially thorough reading of abstracts of each literature is conducted to identify the relevance of literature to our study. In consequent steps, proof reading to journals and papers were done and certain literature were eliminated which were not relevant to the objectives of study.

In next section, Discussion of the content of the scientific literature on collaborative robots is elaborated which broadly classified into two groups viz. Safety and Ergonomics. Further each group is classified into two sub clusters (Fig. 4).

2.1 Safety

"It's impossible for a robot to hurt a human being" and "A robot cannot, through its inaction, enable a human being to endanger himself" are the first and third laws of robotics, respectively. This emphasizes how crucial safety is with the evolution of industrial cobots, robots are now capable of working alongside humans and performing tasks in close proximity. However, doing so necessitates disregarding security protocols and eliminating human–robot physical separation. The fast movement and use of dangerous tools by robots can pose a threat to humans. Moreover, in extreme environmental conditions or in case of system failure, the dangerous behavior of these systems can lead to catastrophic consequences.

Authored by De Santis and Siciliano's the paper provides a comprehensive review of safety issues related to human–robot cooperation in manufacturing systems. The authors identify four main categories of safety issues: physical safety, functional safety, social safety, and psycho safety. One of the key contributions of the paper is its emphasis on the need for a comprehensive, multidisciplinary approach to addressing safety issues in human–robot collaboration [1].

Bicchi et al. discuss the safety issues related to the increasing trend of physical interaction between humans and robots. Author proposes the concept of "safe robot behavior" which is based on the robot's ability to sense the environment, monitor its own actions, and adjust them to ensure safety. The authors further discuss the various factors that influence the safety of physical human–robot interaction, such as the level of interaction, the type of task, the environment, and the human operator's experience and skills. The chapter concludes by presenting various approaches and technologies

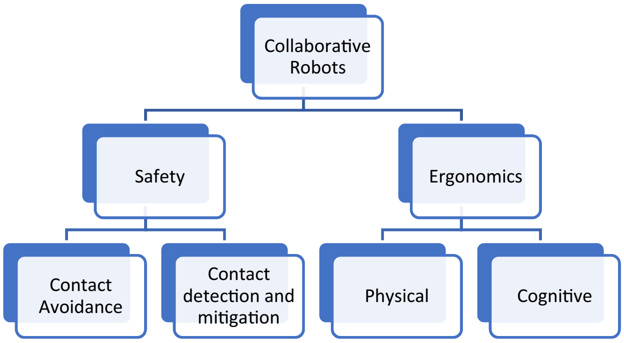


Fig. 4 Identification of groups and subgroups

that can be used to enhance the safety of physical human–robot interaction, such as compliance control, force feedback, and proximity sensors. The authors underline the importance of further research and development in this field to ensure safe and effective human–robot collaboration [2].

Wang et al. provided a brief review of safety strategies for physical human–robot interaction (PHRI). They highlighted the importance of developing safety measures to ensure that PHRI can be integrated safely into various applications, including manufacturing, healthcare, and home assistance. The authors identified various types of safety strategies, including mechanical, electrical, and software-based measures. They also discussed the importance of integrating sensing and monitoring systems into PHRI applications to detect and react to any potential collisions or hazards [3].

The International Organization for Standardization (ISO) published a technical study called ISO 10218-2:2011 that details the safety standards for industrial robots and robotic devices, specifically the robot systems and integration. This standard offers instructions for designing, installing, running, and maintaining robotic systems, together with the necessary safety precautions for human–robot interaction (HRI). The report includes provisions for both functional and environmental safety, including protection against electric shock, fire, and explosion, and requirements for emergency stop functions, protective barriers, and safety interlocks. The standard also provides guidelines for risk assessment and reduction, as well as for the design and verification of safety-related control systems [4].

The paper by Gualtieri et al. discusses how to create collaborative assembly workstations that are both safe and ergonomic while also meeting the demands of production efficiency; system integrator designers need new design criteria. In this article, design rules and prerequisites are collected and categorised based on international standards, research, and actual use cases. This effort will aid in the future creation of a simple technique for the assessment of both new design concepts and applications based on the fulfilment of several criteria listed in a tick list. From the perspective of occupational health and safety, this check list will also give a preliminary assessment of how well certain of the required Machinery Directive standards have been met [5].

Further, safety of cobotics system in divided into two broad categories.

2.1.1 Contact avoidance

The idea of Contact Avoidance focuses on preemptively addressing the mechanical risks to operators by implementing preventive methods and systems to avoid hazardous contact. The ultimate goal is to prioritize the safety of the operators in industrial settings where they are working alongside machinery and equipment.

Schmidt and Wang et al. proposed a novel approach for active collision avoidance in human–robot collaboration scenarios. Their work focused on the development of a collision detection and avoidance system that uses force feedback to adjust the robot's trajectory in real-time. The proposed system consisted of three main components: a force sensor, a control unit, and a collision avoidance algorithm [6].

Chablat and Girin et al. developed an industrial security system that ensures safe and secure human–robot coexistence in manufacturing environments. The authors proposed an industrial security system that combines a range of sensing technologies, including cameras, laser scanners, and pressure sensors. The system is designed to detect the presence of humans in the robot's workspace and respond accordingly [7].

Bedolla and Belingardi et al. addressed the challenge of developing safe and efficient human–robot collaboration (HRC) assembly process in the automotive industry. The authors proposed a safety design framework that consists of three main phases: risk assessment, safety design, and safety verification. The risk assessment phase involves identifying and evaluating the risks associated with the HRC assembly process, such as collisions or entrapment. The safety design phase involves developing safety measures and controls to mitigate the identified risks, such as force-limited operation or proximity sensors. The safety verification phase involves testing and validating the effectiveness of the safety measures and controls [8].

Authored by Chen et al. the paper presents an approach to object recognition within the context of human–robot shared workspace collaboration. They propose a new approach based on deep learning algorithms, which can automatically learn and recognize objects in real-time [9].

The paper by De Luca and Flacco et al. discusses an integrated control approach for PHRI. The authors emphasize the need for effective collision avoidance, detection, reaction, and collaboration in order to ensure safety during human–robot interaction. The proposed control approach is based on a combination of active and passive compliance control. The authors also describe the use of vision and force feedback sensors to improve situational awareness and to enable the robot to adapt its behavior in real-time based on the human's actions [10].

Fiacco et al. presented a depth space approach for evaluating the distance to objects in a human–robot collaborative workspace. The "Depth space," is a metric space that represents the distances between the robot and objects in the workspace. They proposed a method for computing depth space using RGB-D data and a mathematical formulation that allows the robot to assess the distance to objects in real-time. The study contributes to the literature on human–robot collaboration by proposing a new approach for evaluating distance to objects in the workspace, which can aid in collision avoidance and ensure the safety of humans and robots working together [11].

Authored by Navarro et al. paper presents a novel approach for achieving safe human–robot interaction based on adaptive damping control. The authors propose an ISO10218-compliant controller for robotic manipulators, which is capable of reducing the damping coefficient during the interaction with a human operator to minimize the risk of injury in the event of a collision. The controller estimates the external force applied by the human operator and adapts the robot's damping coefficient accordingly to limit the collision force. The authors evaluate the performance of the proposed controller using a KUKA robot arm and a force/torque sensor [12].

Authored by Morato et al. proposed a framework for safe human–robot collaboration using multiple kinects for real-time human tracking. The proposed framework integrated the RGB and depth information of multiple Kinects to create a 3D model of the workspace and the humans present in it. The 3D model was then used to track the human movements in real-time, and the robot was programmed to respond accordingly. The study suggests that the use of multiple kinects for real-time human tracking can significantly improve the safety of human–robot collaboration. However, the study did not address the limitations of the kinect technology, such as occlusions, accuracy issues, and noise in the depth data, which could affect the reliability of the proposed framework in practical settings [13].

Authored by Avanzini et al. proposed a novel approach for safety control of industrial robots using a distributed distance sensor. The proposed solution involved the use of a network of sensors that can detect the proximity of any obstacle or person within the robot workspace. The system was designed to operate in real-time and provide continuous feedback to the robot controller, allowing it to adapt its movements and speed to avoid any potential collision. The results showed that the distributed distance sensor was able to detect obstacles accurately and provide timely feedback to the robot controller, allowing it to modify its movements and avoid collisions [14].

Authored by Bdiwi et al. presents a strategy for ensuring the safety of human–robot interaction in industrial settings. The proposed strategy involves dividing the interaction between the human and the robot into three levels: low, medium, and high. For each level, the authors propose specific safety measures that should be implemented to ensure the safety of humans during the interaction. These measures include limiting the speed and force of the robot, using proximity sensors to detect the presence of humans, and implementing emergency stop systems [15].

2.1.2 Contact detection and mitigation

The idea of Contact Detection and Mitigation is focused on ensuring the safety of operators in terms of mechanical risk by reducing the energy exchanged during unexpected or accidental contact between humans and robots. This is accomplished through the implementation of systems and methodologies aimed at detecting and mitigating such collisions.

Authored by Heo and Lee et al. the paper proposes a deep learning-based approach to collision detection for industrial collaborative robots. The authors propose a deep learning-based approach that uses convolutional neural networks (CNNs) to predict collisions between the robot and its environment. They train the CNN on a dataset of simulated collision scenarios, and demonstrate that the model can accurately predict collisions in real-time with low computational overhead [16].

Authored by Wang et al. the paper presents an overview of the state-of-the-art technologies and approaches for implementing physical human–robot interaction (pHRI) such as force sensing, tactile sensing, and vision-based sensing in collaborative manufacturing systems. To evaluate the effectiveness of pHRI in manufacturing, the authors conducted a case study involving a collaborative assembly task. The study involved the use of a force-sensing and camera-sensing robot to work alongside human workers in the assembly of a product [17].

Authored by Liu et al. the paper presents a collision detection and identification method for robot manipulators based on an extended state observer (ESO). The authors propose a collision detection and identification method based on an ESO. The ESO is used to estimate the state of the robot manipulator, including the position, velocity, and acceleration. By comparing the estimated state with the expected state, the method is able to detect and identify collisions [18].

The paper by Schiavi et al. discusses the integration of active and passive compliance control for ensuring safe human–robot coexistence. The authors argue that active compliance control can ensure safety during interactions with high forces or impacts, while passive compliance control can provide stability and safety during interactions with low forces or impacts and presents a hybrid controller that combines both active and passive compliance control and allows for safe interaction with a human operator [19].

Authored by De Luca et al. the paper focuses on the development of a lightweight manipulator arm equipped with sensors to detect potential collisions and to react appropriately to prevent damage to the robot and injury to humans. The paper describes the collision detection system which is based on a combination of force and torque sensors, and visual information from cameras mounted on the robot. The authors also propose a safe reaction algorithm to avoid or minimize the impact of collisions [20].

Authored by Haddadin et al. the paper provides an in-depth review of the collision detection and reaction approaches for ensuring safe physical human–robot interaction. The authors present a novel approach for collision detection and reaction using three-layer safety architecture. The first layer is the control layer, which monitors the robot's motion and signals an alarm in the event of a collision. The second layer is the decision layer, which evaluates the severity of the collision and triggers the appropriate safety measure. The third layer is the reaction layer, which executes the safety measure and stops the robot in case of an emergency [21].

Authored by De Benedictis et al. proposed a control strategy for regulating force impulses during human–robot interactions. The authors proposed a control strategy based on impedance control, which uses a combination of force and position control to regulate the force impulse during an impact. The proposed method was implemented and tested using a robotic manipulator and a force sensor. The results showed that the proposed strategy effectively regulated the force impulse during impact, leading to improved safety during human–robot interactions [22].

The paper by Indri et al. presents a collision detection method between an industrial robot and its environment. The approach consists of three main steps: first, the environment is modeled using a mesh structure; second, the robot is represented as a set of convex polyhedral; and finally, collision detection is performed using an efficient algorithm that takes into account the relative motion between the robot and the environment. Experimental results demonstrate that the effectiveness of the proposed approach and on comparison approach found to be more efficient [23].

Authored by Lee and Song et al. the paper proposed a novel method for detecting collisions between a robot manipulator and its surroundings without the need for sensors. The proposed method utilizes a friction model to estimate the contact force between the robot manipulator and the environment. This force is then used to detect collisions based on a threshold value set by the user. The authors tested the method on a three-axis robot arm and showed that it was able to successfully detect collisions with high accuracy and without the need for additional sensors [24].

Authored by Ren and Dong et al. presented a new approach for collision detection and identification of robot manipulators based on an extended state observer (ESO). The proposed method used the ESO to estimate the external disturbance caused by the collision and identified the collision parameters, including the collision position, direction, and magnitude. The main contribution of this work is the use of an ESO for collision detection and identification of robot manipulators [25].

2.2 Ergonomics

Ergonomics is the study of designing work environments and systems that are optimized for human use. Collaborative robots are designed to work safely and effectively with human workers in a shared workspace. Therefore, ergonomics is essential in the design and implementation of collaborative robots for several reasons such as Safety, Efficiency, Comfort, Productivity and Adaptability. Overall, the importance of ergonomics in collaborative robots cannot be overstated and leads to better outcomes for both human and robot workers.

Bortot's et al. focuses on the ergonomic aspects of human–robot coexistence in the context of production. The thesis identifies several key ergonomic factors that are important for ensuring safe and effective human–robot collaboration in production settings. These include physical factors such as the design and placement of robotic systems, as well as cognitive and social factors such as the level of automation and the quality of communication between humans and robots [26].

Authored by Fraboni et al. focus of this article is on establishing secure and productive human–robot collaborations, which help us, understand how to implement and evaluate collaborative robotic systems in organizations. This means that the interaction between people and cobots should be planned and carried out in a way that minimizes hazards to employees while still increasing system performance and productivity. In general, successful human–robot collaboration entails finding a balance between protecting workers' physical and mental health and reaching the appropriate levels of productivity and performance. The study emphasizes crucial tactics for assuring employees' psychological well-being, maximizing performance, and fostering the seamless integration of new technology. This has broad implications for sustainability in organizations [27].

2.2.1 Physical ergonomics

Physical Ergonomics in the field of human–robot interaction in industrial settings involves reducing biomechanical workload through the use of collaborative robots as advanced tools, aimed at improving the physical well-being of the operators.

Authored by Sadrfaridpour and Wang et al. proposes an integrated framework for HRI in collaborative assembly tasks within Hybrid manufacturing cells which consists of three key components: task planning, motion planning, and control. The task planning involves determining the optimal sequence of tasks for the human and robot, taking into account factors such as task complexity and worker/robot capabilities. The motion planning involves generating trajectories for the robot and human worker to perform their respective tasks, while ensuring that collisions are avoided and the task is completed efficiently. The control involves implementing feedback control to ensure that the robot and human worker perform their tasks accurately and effectively [28].

Authored by Cherubini et al. the paper presents a framework for collaborative manufacturing pHRI which consists of three main components: task planning, pHRI control, and safety monitoring. The task planning involves determining the optimal sequence of tasks for the human worker and robot to perform, taking into account factors such as task complexity and worker/robot capabilities. The pHRI control involves implementing feedback control to ensure that the robot and human worker perform their tasks accurately and effectively, while ensuring that the human worker is not at risk of injury. The safety monitoring involves continuously monitoring the environment and behavior of the human worker and robot to ensure that any potential safety risks are identified and mitigated [29].

Authored by Dannapfel et al. the paper presents a systematic planning approach for enabling heavy-duty human–robot cooperation in the automotive flow assembly process which consists of five main steps: (1) process analysis and classification, (2) task allocation, (3) workspace design, (4) robot selection, and (5) safety analysis [30].

The Robonaut is a humanoid robot designed for working in space environments with astronauts. Bluethmann et al. present the development of Robonaut and its potential applications in space missions. The robot's design includes human-like arms, hands, and fingers that can mimic human movements and perform complex tasks. The robot is also equipped with sensors, cameras, and computer vision systems that allow it to interact with its environment and perform various tasks. The paper discusses the design challenges associated with creating a humanoid robot for space missions, including the need to ensure safety, reliability, and compatibility with the existing space infrastructure [31].

Authored by Müller et al. investigates how collaborative robots (cobots) can be integrated into assembly lines and how they can work together with human workers to increase efficiency and productivity. The authors analyzed the assembly tasks and identified those that could be performed by robots and those that required human involvement. The study proposed a process-oriented task assignment algorithm to determine what tasks are expected to the robot and what tasks are expected by the human worker. The algorithm takes into account the complexity of the task, the skill level of the worker, and the robot's capabilities [32].

Maurice et al. present a literature review on human-oriented design for collaborative robots. They begin by defining the characteristics of cobots and highlighting the challenges involved in designing them. They then discuss the various design considerations that must be taken into account when creating cobots that are safe and easy to use. These include the robot's size, weight, speed, and mobility, as well as its sensing and control capabilities. The authors then discuss several case studies that illustrate how human-oriented design can be applied in practice. They also discuss the use of motion capture technology to develop cobots that can mimic human movements and collaborate with workers in real-time [33].

Authored by Heydaryan et al. the article discusses implementation of a HRC system in an automotive assembly line. The authors present the safety measures adopted for the system design and development to ensure the protection of the human operator during the collaboration process. It then introduces the case study of a real-world HRC assembly process in the automotive industry, and the safety design strategies and tools applied during the development of the system [8].

The paper by Tang and Webb et al. paper presents a gesture control system that allows operators to control robots without physically touching any interface. The authors suggest that this system may improve ergonomics and reduce the risk of repetitive strain injuries. The authors describe the design of their system, which is based on a combination of depth cameras and machine learning algorithms. The system uses the cameras to capture and interpret the operator's gestures in real time, and then uses this information to control the robot's movements [34].

Authored by Faber et al. article presents a method for generating assembly plans that take into account the cognitive capabilities of human workers and the physical capabilities of robotic collaborators. The authors propose a planning framework that incorporates information about the tasks to be performed, the characteristics of the human workers, and the capabilities of the robots, with the aim of creating assembly sequences that are both ergonomic and efficient [35].

2.2.2 Cognitive ergonomics

Cognitive ergonomics pertains to minimizing mental stress and psychological discomfort for operators while working alongside robots. This principle is essential in ensuring interaction acceptability. Additionally, physical ergonomics focuses on reducing biomechanical workload and improving operators' physical well-being by utilizing collaborative robots as advanced tools. Organizational ergonomics, on the other hand, aims to optimize social-technical systems in terms of organizational structures, policies, and processes. By improving these factors, organizations can facilitate safe and efficient collaboration between human workers and robots.

Authored by Long et al. the paper presents an industrial security system designed to ensure safe human–robot coexistence in an industrial environment. The authors propose an industrial security system that includes three main components: a secure communication protocol, a secure operating system, and a secure monitoring system. The secure communication protocol is designed to prevent unauthorized access to the robot system by using encryption and authentication mechanisms. The secure operating system is designed to prevent malware and other attacks on the robot by enforcing strict security policies and isolating the robot's software environment from other systems. The secure monitoring system is designed to detect and respond to security breaches in real-time by analyzing system logs and monitoring the behavior of the robot and human operators [7].

Authored by Faber et al. the paper presents an approach to enhance human–robot collaboration in self-optimizing assembly cells by incorporating cognition into assembly sequence planning. The author proposes a cognition-enhanced assembly sequence planning approach that incorporates cognitive models of human behavior into the planning process. The approach uses a cognitive architecture called ACT-R (Adaptive Control of Thought-Rational) to model human behavior and simulate the performance of assembly tasks in collaboration with robots [35].

Solvang and Sziebig's et al. paper presents a review of the literature on the use of industrial robots in cognitive info-communication. The paper explores the potential for robots to function as cognitive systems that can interact with humans in complex manufacturing environments. The author explains the concept of cognitive info-communication, which refers to the exchange of information and knowledge between humans and machines. They argue that cognitive info-communication is critical for effective human–robot collaboration in manufacturing, as it enables robots to understand and respond to human intentions and goals [36].

Authored by Shravani and Rao et al. discusses the challenges faced by industries while introducing robots and automation without creating fear of unemployment and high costs. The review included studies on the social and psychological impact of automation on the workforce and the economy. The framework also emphasizes the need for creating a supportive work environment that encourages human–robot collaboration and facilitates the transition to a more automated workplace [37].

Authored by De Santis' et al. the paper presents literature review focuses on the modeling and control of physical and cognitive aspects in human–robot interaction (HRI). The paper explores the current state of HRI research and the challenges faced in modeling and controlling robot behavior in physical and cognitive aspects to improve human–robot collaboration. The author discusses the need for robots to have cognitive capabilities to facilitate communication and collaboration with humans in different environments. The review emphasizes the importance of designing robots that can adapt to different tasks and environments while ensuring the safety and comfort of humans [38].

Authored by Medina, Lorenz, and Hirche et al. the paper proposes a new approach to human–robot collaboration based on anticipatory haptic assistance. The paper presents a framework for human–robot collaboration that incorporates anticipatory haptic assistance, based on a stochastic model of human behavior. The authors then describe how this framework can be used to synthesize appropriate haptic cues that help guide the human operator towards a desired task outcome [39].

Authored by Matsas et al. presents a prototyping approach for proactive and adaptive techniques for human–robot collaboration in manufacturing using virtual reality. The authors propose a methodology for designing and evaluating human–robot collaborative tasks that integrates the use of virtual reality simulations and machine learning techniques. The paper focuses on the development of a proactive and adaptive approach to haptic feedback for collaborative tasks, which takes into account the uncertainty in human behavior [40].

Authored by Maurtua et al. discusses the key issues and challenges of human–robot collaboration in industrial settings, with a focus on safety, interaction, and trust. The authors provide an overview of various safety measures that can be taken to ensure safe HRC, including safety sensors and safety controllers. They also discuss the importance of communication between humans and robots, highlighting the need for robots to be able to understand human intentions and for humans to trust the robot's actions [41].

Authored by Charalambous et al. aimed to identify the key organizational human factors that influence the introduction of human–robot collaboration (HRC) in industry. The study involved semi-structured interviews with industry experts who had experience in HRC implementation… These factors included organizational culture, management support, employee involvement and training, job design, and communication. The authors noted that these factors were interrelated and had an impact on each other [42].

Authored by Rahman and Wang et al. proposes a framework for subtask allocation in human–robot collaboration based on mutual trust. The proposed framework is composed of three primary modules: the communication, the trust evaluation, and the subtask allocation. The authors validate their framework through simulation and experiments on a lightweight assembly task. The findings indicate that the proposed framework leads to enhanced collaboration performance and increased mutual trust between the human and robot [43].

Authored by Koppenborg et al. investigation into how human–robot collaboration in an industrial setting is impacted by movement speed and predictability. The author conducted a study with 32 participants who were instructed to put something together collaboratively with a robot. The authors concluded that movement speed and predictability are important factors to consider when designing human–robot collaboration systems in industrial settings, and that slower and more predictable robot movement can improve performance and perceived safety and trust [44].

3 Discussion

In this section, we will begin by presenting and analyzing the descriptive findings of our study. We will then proceed to examine the results derived from the content analysis, aiming to identify the most prominent research themes that have emerged within the field of safety and ergonomics in industrial collaborative robotics. Lastly, we will acknowledge and discuss the limitations associated with this study.

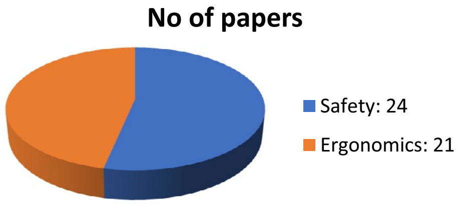
In total, 45 papers were analyzed in detail, with the following breakdown for each cluster, the total number of publications classified (including papers classified in additional clusters):

For Contact Avoidance 10 papers, 10 papers for Contact Mitigation and, 4 papers covering both contact avoidance and detection and mitigation of contacts.

One paper for Physical and Cognitive and Organizational Ergonomics, nine papers for Physical Ergonomics and, 11 papers for Cognitive and Organizational Ergonomics.

According to Fig. 5, 53.33% of the publications found are about "safety," while 46.66% are about "ergonomics." This indicates that contemporary researchers made investments in. More work should be put into developing safety measures rather than researching HRI ergonomics situations.

Fig. 5 Number of papers



3.1 Challenges and future development

In this segment, Based on the most important and intriguing research themes found in each cluster, we highlight the limitations of our analysis and suggest options for future research.

3.1.1 Safety

Regarding safety in Human–Robot commerce (HRI), the primary ideal is to guard drivers from unlooked-for collisions between mortal body corridor and robot systems or workspace rudiments, while contemporaneously icing optimal performance of product systems.

Contact Avoidance crucial exploration themes that hold significance and pledge for Contact Avoidance includes Motion Planning and Control, Sensor Systems for Object Tracking, and Safety Management. These findings affirm the prevailing trend of developing safety systems that prioritize driver protection through preventative ways. Accordingly, a coordinated integration of vision systems, robot control, and line planning methodologies becomes pivotal. Safety Management also assumes significance as it supports the operation and evaluation of proposed safety measures, enabling better collision vaticination and minimizing the liability of similar incidents.

Contact Discovery and Mitigation Notable exploration themes for Contact Discovery and Mitigation comprise Motion Planning and Control, Robot System Design, and detector systems for contact operation. These themes parade essential correlations as advancements in protection- grounded safety measures bear concurrent development in robot tackle, contact discovery detector systems, and line planning. Similar combined sweats grease effective collision operation and reduce associated consequences.

3.1.2 Ergonomics

The part of ergonomics in HRI involves aiding humans in reducing biomechanical and cognitive load associated with work, without introducing new health and safety hazards stemming from relations with robot systems.

Fitness Ergonomics Task Scheduling (of high significance) and Motion Planning and Control (of moderate significance) are two important investigation subjects for physical ergonomics. These findings are consistent with the idea of human-centered workspaces supported by sophisticated robotization technologies. The creation of adaptive real-time task scheduling, as well as motion planning and control, should be given priority by unborn exploration. By adapting work cycles and robot system performance based on drivers' physical conditions (e.g. anthropometric features, age, gender, dominant branch, special limits or disabilities, weariness, etc.), these developments would facilitate workload reduction. Such a strategy aids in the implementation of sustainable product systems, improves the welfare of drivers, and makes it possible to hire older or otherwise disadvantaged workers. Still, it calls for the gathering of specific real-time data relating to drivers' psychophysical states.

Metrics and Tests, Motion Planning and Control, and Simulation and Modeling are some of the main research areas in cognitive ergonomics. Cognitive aspects should concentrate on minimizing work- related psychosocial pitfalls arising from participated conditioning and workspaces. Also, icing the adequacy of robot systems by mortal associates is pivotal. Balancing the advantages and implicit discomfort associated with varying degrees of commerce becomes essential. Methodologies for assessing and testing cooperative systems could prop in relating and mollifying implicit sources of psychosocial pitfalls. Also, the design of crucial features and performance related to cooperative systems should consider these aspects. Simulations and modeling play a vital part in supporting and validating these design choices.

3.1.3 Other challenges

1. A cobot must be built similarly to a traditional robot in order to maximize task execution quality, the ergonomics of a human coworker, and ensure his safety.
2. Millions of artificial robots have been used in production environments across the globe. Therefore, it would be more desirable to develop technologies that can transform them into mortal-safe robotic systems with no attack variations rather than replacing all of these traditional robots with safe cobots at a huge expense. Reprogram capability, scalability and literacy capability of cooperative robots is also a big challenge. On the same line, erecting a stoner-friendly mortal—robot interfaces come up with a challenge.

3. Real- time constraints are a critical aspect of mortal- robot commerce (HRI) in the realm of artificial cobotics. Meeting these constraints is essential to insure the trust ability and effectiveness of the system. When calculations exceed predefined thresholds, it can affect in- deterministic geste and potentially lead to system failures with severe consequences. These limitations have significant counteraccusations for colorful aspects of HRI, including mortal action recognition, contemporaneous discovery of multiple conduct, anti-collision strategies, control armature, and 3D vision.
4. A significant challenge in the advancement of mortal- robot commerce (HRI) within artificial cobotic systems is the fault- forbearance paradigm. This paradigm aims to incorporate individual capabilities André-planning capacities, allowing the system to acclimatize stoutly grounded on the available coffers and trustability. Expansive exploration has been devoted to the fault forbearance model, but a comprehensive approach that seamlessly integrates this paradigm into the design of HRI and control infrastructures is still lacking.
5. There are colorful constraints and challenges associated with artificial cobotic systems that need to be addressed. These include achieving dependable discovery of mortal stir to enable the development of accurate prophetic systems, icing robust discovery of contact between robots and humans in multiple locales, and developing responsive regulators able of real- time liner-planning in complex and cluttered surroundings.

3.2 Summary of the discussion

According to the statistics, the most cutting-edge debate subjects for contact avoidance are Safety Management, Sensor Systems for Object Tracking, and Motion Planning and Control. Case studies, operations, help systems, and artificial intelligence all have minimal effects. The main themes of Motion Planning and Control include Mortal-stir Vaticinator, Line Modification, and Stir Control Techniques. The main topics covered in Sensor Systems for Object Tracking include the creation and fusion of monitoring and computer vision systems for gesture recognition, workplace management, and human localization. The design of methods, standards, and guidelines for connection obstruction operation is one of the main themes in safety management.

The statistics show that Motion Planning and Control, Robot System Design, and sensor systems for contact operation are the most cutting-edge dissertation issues for Contact Discovery and Mitigation. Case studies, operations, safety management, simulation and modeling provide only minor contributions. The primary topics for Motion Planning and Control are control strategies. The development of robot attack and design methods is the focus of Robot System Design. The development of sensor bias and methodology for discovery are the primary contents for sensor systems for contact operation.

Task Scheduling Strategy is the most sophisticated physical ergonomics discourse theme, according the data. Motion Planning and Control and Assistance Systems provide a small contribution. The main focus of Task Scheduling Strategy is on assigning and organizing robot-

Human task sequences while incorporating physical ergonomics.

Metrics and Tests, Motion Planning and Control, and Simulation and Modeling appear to be the most sophisticated discussion themes for Cognitive and Organizational Ergonomics. Task scheduling strategy and assistance systems provide insignificant contributions. The development of an evaluation technique for robot acceptability and the establishment of an organizational framework for effective HRI operations performance are the major topics covered in Metrics and Tests. The primary topics for Motion Planning and Control are control tactics connected to cognitive components of HRI. The creation of virtual reality exploitation for the assessment of the cognitive aspects of HRI is one of the key topics covered in Simulation and Modeling.

The current trend in artificial cobotics is concentrated on developing flexible systems that enable safe and cooperative relations between humans and robots to negotiate colorful tasks. This growing trend encourages diligence to consider integrating similar cobotic systems into their being manufactories. In the coming times, cobots are anticipated to play a pivotal part and become the dominant technology for named operations, potentially filling the maturity of the remaining 90 of workstations. It’s worth noting that a significant number of exploration studies have been devoted to addressing safety and security enterprises in cobotic systems, exercising different technologies and approaches to insure the well- being of mortal workers and the overall system integrity.

Table shown below Tables 2 and 3 concisely represents the entire summary of review of safety and ergonomics consisting both sub clusters for each.

Table 2 Summary of literature related to Safety cluster of Collaborative robots

Author name	Year	Sub-cluster	Description
De Luca	2006	Contact detection and mitigation	Collision detection system based on a combination of force and torque sensors, and camera sensor
Bicchi	2008		Safety for physical human–robot interaction
Haddadin	2008	Contact detection and mitigation	Approach for collision detection and reaction using a three-layer safety architecture
De Santis and Siciliano's	2008		Types of safety issues (Physical safety, functional safety, social safety, and psycho safety)
Schiavi	2009	Contact detection and mitigation	Integrated active and passive compliance monitoring to ensure safe human–robot coexistence
De Luca and Flacco	2012	Contact Avoidance	Collision avoidance based of active and passive compliance control
Avanzini	2014	Contact avoidance	Industrial robot safety regulation utilising a distributed distance sensor
Morato	2014	Contact avoidance	Utilising several Kinects for real-time human identification, a framework for secure human–robot collaboration
Flacco	2015	Contact avoidance	Depth space approach determines the distance between items in a shared workspace for humans and robots
Indri	2015	Contact detection and mitigation	A common approach for detecting collisions between an industrial robot and its surroundings
Lee and Song	2016	Contact detection and mitigation	Robot Manipulator Collision Detection Based on Friction Model Without Sensors
Navarro	2016	Contact avoidance	Control of adaptive damping for secure human–robot interaction
Young Jin Heo and Woongyong Lee	2016	Contact detection and mitigation	Convolutional neural networks (CNNs) to predict collisions between the robot and its environment
Liu	2016	Contact detection and mitigation	Robot manipulator collision detection and identification using an extended state observer
Mohamad Bdiwi and Marko Pfeifer	2017	Contact avoidance	Strategies of safety function, Classification of HRI level
Schmidt and Wang	2017	Contact avoidance	Collision avoidance using force feedback
De Benedictis	2017	Contact detection and mitigation	A control strategy for regulating force impulses during human–robot interactions
Chablat and Girin	2018	Contact avoidance	Industrial security system comprised of cameras, laser scanners, and pressure sensors
Xi Chen	2018	Contact avoidance	Deep learning algorithm for real time object detection
Xi Vincent Wang	2020	Contact detection and mitigation	State-of-the-art technologies and approaches for implementing pHRI such as force, tactile, and vision-based sensing
Bedolla and Belingardi	2018	Contact avoidance	Safety design framework(risk assessment, safety design, and safety verification)
Wang, Zeng, and Geng	2019		Review of safety methods for physical human–robot interaction (PHRI)
Ren and Dong	2019	Contact detection and mitigation	An extended state observer (ESO)-based novel method for robot manipulator collision detection and identification
Luca Gualtieri	2020		Guidelines will support application designers to proper develop and evaluate safe, human centered and efficient collaborative assembly
ISO 10218-2:2011			Technical report

Table 3 Summary of literature related to Ergonomics cluster of Collaborative robots

Author name	Year	Sub-cluster	Description
Bluethmann	2003	Physical ergonomics	Presents the development of Robonaut (a space robot) and its potential applications in space missions
De Santis'	2008	Cognitive ergonomics	Literature review focuses on the modelling and control of physical and cognitive aspects in human–robot interaction
Solvang and Sziebig's	2012	Cognitive ergonomics	Explains the concept of cognitive info-communication, which refers to the exchange of information and knowledge between humans and machines
Bortot's	2014		Focuses on the ergonomic aspects of human–robot coexistence in relation to production
Charalambous	2015	Cognitive ergonomics	Identifies the key organizational human factors that influence the introduction of human–robot collaboration
Long	2018	Cognitive ergonomics	Proposed an industrial security system (a secure communication protocol, a secure operating system, and a secure monitoring system)
J.R. Medina, T. Lorenz, and S. Hirche	2015	Cognitive ergonomics	Presents a framework for human–robot collaboration that incorporates anticipatory haptic assistance, based on a stochastic model of human behaviour
Dannapfel	2016	Physical ergonomics	Outlines a methodical planning strategy for enabling robust human–robot collaboration during automotive assembly
Müller	2016	Physical ergonomics	Investigates how collaborative robots can be integrated into assembly lines and how they can work together with human workers
Maurice	2017	Physical ergonomics	Presents a literature review on human-oriented design for collaborative robots
Cherubini	2016	Physical ergonomics	Presents a framework for collaborative manufacturing pHRI(task planning, pHRI control, and safety monitoring)
Faber, Mertens, and Schlick's	2017	Physical ergonomics	a strategy to improve human–robot cooperation in self-optimizing assembly cells by introducing cognition into the planning of assembly sequences
Maurtua	2017	Cognitive ergonomics	Collaboration between humans and robots in industrial applications requires safety, interaction, and trust
Koppenborg	2017	Cognitive ergonomics	examined how movement predictability and speed affect human–robot collaboration
Matsas	2018	Cognitive ergonomics	An approach to prototype proactive and adaptive methods for virtual reality-based human–robot collaboration
Heydaryan	2018	Physical ergonomics	Presents the safety measures adopted for the system design and development to ensure the protection of the human operator during the collaboration process
Tang and Webb	2018	Physical ergonomics	Presents a gesture control system that allows operators to control robots without physically touching any interface
Shravani and Rao	2018	Cognitive ergonomics	Study of the social and psychological impact of automation on the workforce and the economy
S.M. Rahman and Y. Wang	2018	Cognitive ergonomics	Presented a plan for subtask allocation in human–robot collaboration based on mutual trust
Faber	2019	Cognitive ergonomics	Planning assembly sequences with cognitive enhancement for ergonomic and human–robot collaboration
Sadrfaridpour and Wang	2020	Physical ergonomics	presents a comprehensive framework for HRI in cooperative assembly activities inside hybrid manufacturing cells
Federico Fraboni	2023		The study emphasizes crucial tactics for assuring psychological well-being, maximizing performance, and fostering the seamless integration of new technology

- Summary of literature related to Safety cluster of Collaborative robots:
- Summary of literature related to Ergonomics cluster of Collaborative robots:

4 Conclusion

Over the past few years, industrial collaborative robotics has attracted a great deal of attention, and human–robot interaction (HRI) has become a vital area of study. This study did a thorough analysis of the literature and developed a tentative classification system, classifying and sub classifying significant works and new research in this field. This study's main goal was to identify and evaluate the burgeoning topics and research problems in safety and ergonomics in industrial collaborative robotics.

For each selected article, a summary was provided, outlining the problem addressed, the proposed approach, the main outcomes obtained, and potential future directions for research. The study also acknowledged the existence of a significant gap between the research carried out in laboratory settings and the practical implementation of cobotic technology in real industrial environments, particularly in the context of smart factories.

The findings of the review indicated that safety was the most extensively explored research category, although ergonomics has witnessed notable growth in recent years. Interestingly, the majority of high-level themes identified were more closely related to safety aspects rather than ergonomics. Within the realm of safety, there was a greater emphasis on prevention rather than protection measures.

Several difficulties and problems encountered by researchers studying HRI in industrial cobots were noted and emphasized towards the end of the work. Considering the continuous growth of the industrial collaborative robot market, these innovations hold promise for the implementation of collaborative production systems that are safe, ergonomic, trustworthy, and efficient.

Author contributions All Authors reviewed the manuscript.

Data availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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