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SAFETY CONSIDERATIONS IN INDUSTRIAL COLLABORATIVE ROBOTS: A REVIEW

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ABSTRACT:

Collaborative robots (cobots), ideal for use alongside humans, can also increase the flexibility of the production system and be introduced gradually in the industrial field. They allow for higher productivity by combining human dynamic problem-solving capabilities and robot endurance and precision. However, in any human-robot collaborative system, the safety of human workers is of the utmost importance. The design of efficient and safe collaborative robot systems is one of the challenges that arise. This paper comprises a narrative literature review that presents a detailed investigation of the existing literature on safety concerns in industrial cobots. It emphasises physical safety and collisions, standards and regulations, risk assessment, sensing techniques, and job ergonomics.

Keywords: Collaborative robots, cobots, industrial safety, human-robot collaboration (HRC), physical safety, risk assessment methodologies, ISO 10218, ISO/TS 15066, sensing technologies, ergonomics

I. INTRODUCTION:

Collaborative robots (cobots) are a major part of the modern revolution in industrial manufacturing. Cobots are specifically designed to co-exist and share workspaces with human workers, thereby enabling physical collaboration with the robot. Cobots have been able to overcome many of the limitations of traditional automation thanks to the evolution of artificial intelligence (AI) and machine learning (ML) technologies that enable them to interact with multiple robots in a human-like way, thereby enhancing their productivity and safety.

The trend toward growing human-robot collaboration and flexible automation, which is driving the rapid adoption of cobots across different industries. In 2023, worldwide, there were 10.5% cobots of the total installed base of robots. They are easily programmed, require no safety infrastructure and allow them to work without physical fencing and integrate into established production areas due to their rapid adoption. The collaborative robot market is predicted to grow at a compound annual growth rate (CAGR) of 32.6% per year from its base until 2030, reaching USD 12.71 billion by 2030.

An advantage of cobots in human-robot collaboration (HRC) is the way they complement one another; for example, humans and machines working together. Humans have proven themselves to be highly adaptable and flexible creatures for handling indeterminate and unpredictable components of work, and robots excel at repetitive tasks with the ability to perform complex tasks with everlasting precision. This synergy has turned cobots into useful tools in many industries. Cobots are also being used in the manufacturing industry to streamline assembly lines, promote more efficient workflows, support employees in tasks that are normally physically demanding, and increase workplace safety.

While cobot technology has many advantages, one important new challenge is ensuring the safety of human employees when cobots are incorporated into shared workspaces. Concerns about safety, trust, and the possibility of human displacement are substantial and must be addressed, highlighting the need to establish robust safety protocols and training to co-exist effectively and safely between human and cobot work areas. As cobot systems come into closer contact with human workers, the risks are also quite different from those in traditional, separated robotic environments, and new frameworks must be developed for risk assessment, sensing, physical safety, ergonomics, and compliance.

International standards are the basis for cobot safety. As presented in the reviewed literature, three ISO standards (ISO 12100, ISO 10218, and ISO 15066) are key to cobot safety, covering general design principles, risk assessment procedures, and specifying the operational constraints for HRC applications, such as force and power limiting (FPL) and speed and separation monitoring (SSM) (Koczi et al., 2022; Matthias et al., 2016). However, there are areas of existing standards that have limitations: ISO 10218 provides little efficiency guidance for the specific requirements of HRC applications (Matthias et al., 2016). The need for ongoing research and evaluation of the safety considerations mentioned above is heightened by the unique regulatory environment and the quick rate of deploying cobots.

Safety work involves collaboration among multiple disciplines in the HRC. In the context of the Industry 4.0 paradigm, in which the manufacturing industry is undergoing a transition from traditional, monodisciplinary approaches to production to more flexible and intelligent forms of automation, the collaboration of humans and robots is becoming a growing topic of interest.

Ensure cobot safety, all the following must be combined: regulatory compliance, use of sensing technologies in real time, and use of adaptive risk assessment methods, along with human-centred ergonomic design. There are specific areas of ongoing research within each of these, and none is yet widely applicable.

This paper, a narrative literature review, explores current research in five principal areas of safety regarding industrial cobot applications: physical safety/collision avoidance, safety regulations and standards, risk assessment approaches, sensing technologies, and workplace safety and ergonomics. This review will integrate the results of all these aspects to gather existing general knowledge of the field, pinpoint missing elements in the studies conducted to date, and develop new methods and protocols for safer and more effective HRC systems.

I.A METHODOLOGY

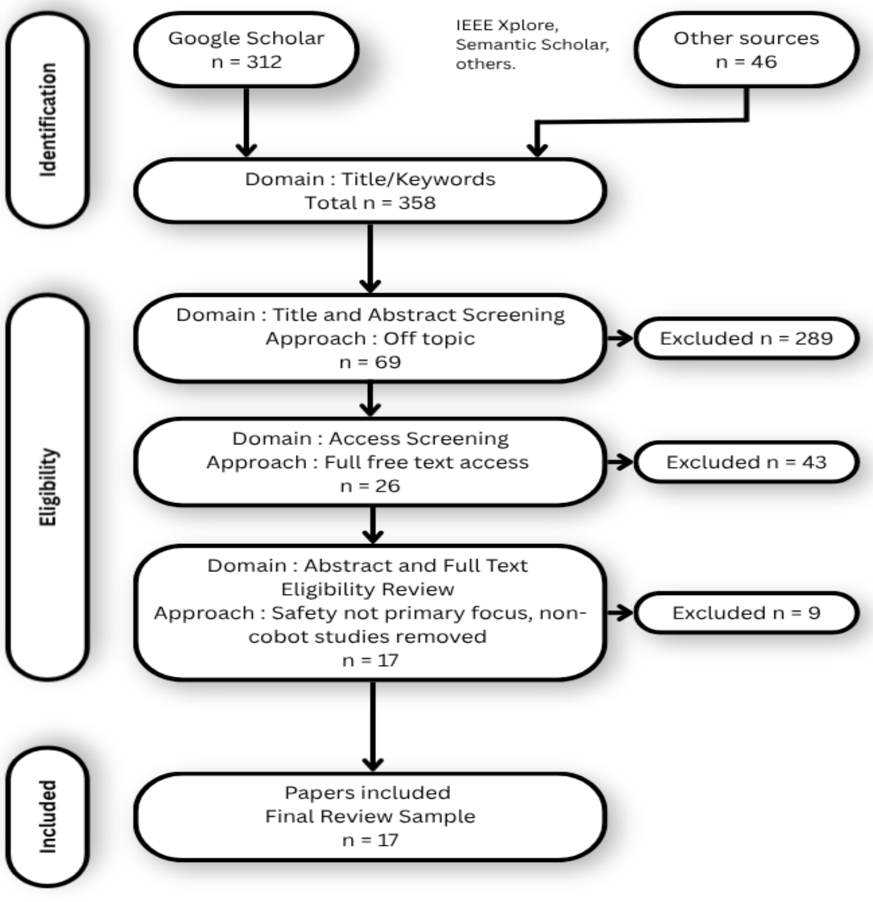
The methodology used in this study was a narrative literature review approach to synthesise the available research on industrial collaborative robot safety considerations. Narrative reviews are usually not systematic reviews; they are not conducted according to stringent, reproducible searches, but are appropriate when a broad overview of a complex, multidisciplinary topic is required, yet the research field is constantly changing. Contributions from many different areas, such as robotics, ergonomics, occupational safety, sensor technology, and standardisation, can be incorporated into the narrative approach.

Search Strategy: Literature was identified using major academic databases, such as IEEE Xplore, Scopus, Web of Science, and Google Scholar. These search terms ranged from various combinations of the keywords "collaborative robots," "cobots," "safety," "human-robot collaboration," "HRC," "risk assessment," "ISO standards," "sensing technologies," "ergonomics," "collision detection, " and "industrial robotics. Peer-reviewed journal articles, conference proceedings, and technical standards published between 2011 and 2025 were targeted. This period was chosen to reflect the trends of cobot safety studies since the publication of the relevant ISO standards about robotics.

Inclusion Criteria: Papers that addressed one or more of the five areas of safety addressed for this review–Physical Safety and Collisions, Safety Regulations and standards, Risk Assessment Methodologies, Sensing Technologies, and Human Factors and ergonomics–were included. Studies providing original research, new methods, or criticism of current methods were given first consideration. These included both original papers that set out important concepts and more recent papers that reflected current research streams.

Limitations of the Methodology: This study is a narrative review that did not use quantitative meta-analysis or systematic quality assessment of papers included. The selection of literature was guided by the authors' experience and expertise, which might create selection bias. However, the narrative approach has allowed the integration of varying opinions and the emergence of topics that may not have been included in systematic reviews with less flexibility. This paper is not meant to be exhaustive or definitive in its scanning of the field but rather as an overview, to provide insights to researchers and practitioners.

II. ANALYSIS OF RESEARCH PAPERS USED IN LITERATURE REVIEW:



III. SIGNIFICANT FACTORS IDENTIFIED:

1. Safety Regulations and Standards: The International Organisation for Standardisation (ISO) guidelines for cobot applications are mainly outlined in ISO 12100, ISO 10218 and ISO/TS 15066. They consist of design principles that specify the limits of force that cobots can transmit during contact and require risk assessment for safer cobot deployment (Kóczi & Sárosi, 2022). Furthermore, they advocate four distinct ways to achieve safe HRC, such as force/power limiting, separation/speed monitoring, safety-rated monitored stop, and hand guiding.

a. **ISO 12100:** This standard includes terminology and methodology for machinery safety based on overall machinery design principles, risk assessment, and risk reduction (Atieh Hanna et al., 2020). The proximity of human workers and cobots makes risk assessment according to ISO 12100 a critical factor when used in HRC applications (Matthias & Reisinger, 2016).

b. **ISO 10218:** Safety requirements are contained in this standard, which includes Part 1 for the manufacture of industrial robots, and Part 2 for the integration of the robot system (Atieh Hanna et al., 2020). The ISO 10218, however, contains insufficient guidance for HRC due to its unique properties (Matthias & Reisinger, 2016).

c. Building on the ISO standards for industrial robots (ISO 10218), ISO/TS 15066 provides additional information required to design safe HRC applications (Matthias & Reisinger, 2016). It offers recommendations in risk assessment for co-robot operation and sets constraints for FPL and SSM HRC applications (Atieh Hanna et al., 2020).

III. 6 Summary of Key Findings Across Domains

Table 1 provides a consolidated summary of the key findings, identified gaps, and future research needs across the five safety domains examined in this review.

Safety Domain	**Key Findings**	**Identified Gaps**	**Future Research Needs**
Physical Safety & Collisions	CCFM methodology improves impact assessment; ISO/TS 15066 collision model oversimplified; biomechanical limits vary across twenty-one body regions	Insufficient experimental data for all body regions; limited validation of CCFM in real industrial settings	Comprehensive impact testing across diverse robot geometries; dynamic collision models accounting for human movement
Safety Regulations & Standards	ISO 12100, 10218, and 15066 provide foundation; four collaborative operation modes defined; standards evolving	ISO 10218 lacks HRC-specific guidance; standards do not address AI/ML integration	Updated standards reflecting Industry 5.0; guidance for adaptive safety systems
Risk Assessment	SAFER-HRC uses formal verification; KSDF enables dynamic risk evaluation; virtual fencing adapts to human movement	Limited validation in real industrial settings; integration challenges	Standardised risk assessment frameworks; AI-enhanced dynamic assessment
Sensing	Multi-modal sensing	Single-sensor	Robust multi-sensor

Technologies	improves safety; FPSD framework shows promise; digital twin integration emerging.	systems still prevalent; limited spatial awareness; short detection ranges.	integration; AI-based sensor fusion; longer-range proximity sensing
Human Factors & Ergonomics	Physical ergonomics reduces WMSD; cognitive ergonomics builds trust; trust calibration improves performance.	Limited integration of ergonomics in safety design; cognitive load measurement challenges	Human-centred design methodologies; real-time ergonomic monitoring

Table 1: Summary of key findings, gaps, and future research needs across safety domains

The results of the synthesis, as displayed in Table 1, show some cross-cutting themes. First, there is a definite shift to dynamic, adaptive solutions and away from static safety parameters. Second, the trend of combining several sensing modalities and AI-powered decision-making is becoming one of the major trends to enhance safety and productivity. Third, the value of human factors, including cognitive ergonomics, is increasingly recognised as a critical component for effective HRC. Lastly, there is a great divide between academic research and industrial implementation, and there is a huge need for translational research, taking theory from the academic world into practice in industry.

1. Physical Safety and Collisions:

A significant observation from our review is that the collision force model in ISO/TS 15066 is unsuitable for calculating impact values, likely due to its simplified basis (Kirschner et al., 2021; Fischer et al., 2023). A CCFM measures the contact sensitivity of a robot in a constrained contact situation based on the collision detection parameters and impact velocity on the robot. The model of the human body according to ISO/TS 15066:2016 [1] includes 21 regions of the human body. A contact stiffness is given for each body region, along with a pain tolerance. A pain onset (in a constrained contact setting) shall not be experienced by reducing the contact force, according to the current technical specification for safe HRC, ISO/TS 15066:2016 (ISO/TS). Contact force in HRC is influenced by various factors, such as robot speed, configuration, robot inertia, surface properties, collision detection methods, and reactions during collision. A practical tool, the CCFM, is presented that aids the implementer of the robot application in determining how to make the application safe while helping him/her to understand the robot collision behaviour (Kirschner et al., 2021).

If maximum safety values are defined for the force or torque of the robot, the values during impact can be minimised because the controller can detect and react earlier to the impact. However, our findings show that these conditions apply to quasi-static contacts or transient impacts based on a static reference. Therefore, this study proposes an experimental assessment of factors that affect the impact pressure and force in the case of a collision between a human and a robot. Crash tests were conducted with different impact points, speeds, and shapes of the impactor, and the findings of these crash tests were compared for the different body areas examined. A significant aspect of our study is the effect of different geometries and their association with different BRs and modelling with different damping Shore hardness on the occurrence of a human-robot collision. It is not always possible to differentiate between the different areas of the body when evaluating safety. The biomechanical pressure limits shown for a region are provided as the lowest limits for the region; it is recommended that they be considered as the threshold value for the entire BR. In safety evaluation, the question of whether the biomechanical limits are respected in these situations is analysed by performing biomechanical measurements. If the biomechanical limits are not exceeded, the project needs to be adjusted to fit within the biomechanical limits to remove or reduce any risk to the human operator (Fischer et al., 2023).

3. SENSING AND DETECTION TECHNOLOGIES:

First, current safety systems include only single-sensor technologies, integrated inside the SSM mode, which involves externally installed structured light cameras. Although there have been advances in on-robot sensing, there have been low-resolution proximity sensors with a maximum range of 30 cm on the robot arm, with only tactile sensing and no shear sensing.

Furthermore, Scholz et al. also indicate that most of the current systems have some drawbacks: They lack spatial awareness and rely on fixed installations, which are not always sufficient for the application of Industry 5.0 technologies. This is confirmed by Amin et al.'s study, which proved that they are not enough alone for intrinsically safe robotic applications, because each of these systems lacks information, and it may result in less productivity and safety.

Second, with sensors to enhance safety and functionality, dual-sensor setups have been trending to boost robustness and fault tolerance. However, multi-sensor systems (greater than three sensors) are still rare, and single-sensor systems remain the most prevalent.

In the studies reviewed, the following multi-modal sensing methodologies were discussed:

a. Amin et al. hypothesise that multi-modal perception can be implemented to interpret human actions, in turn enhancing safety in HRC. Their safety framework utilises visual perception, used for “human action recognition (HAR)”, and tactile perception, used to determine the nature of contact, with the aim of avoiding collisions by interpreting human intention. The system can be used to maintain safe distances between cobots and human workers using HAR, while having the additional benefit of being able to distinguish between deliberate and accidental contact during collision detection. The system integrates deep learning and convolutional neural networks (CNN) to increase robot awareness about human intention during physical contact in real-time, achieving a suitable balance between safety and productivity (Amin et al., 2020).

b. Choi et al. presented the idea of "Flexible Protective Separation Distance (FPSD)" methodology, which is to be used for the optimisation of workspace safety and productivity, considering real-time separation monitoring and safety response. The system should tackle the limitations of existing SSM systems, including fixed safety parameters that cannot be dynamically adjusted when dealing with safety systems. The framework simulates the workspace into a virtual domain through multiple modes of sensing, AI-based safety control mechanisms, and “digital twin” based modelling. The digital twin allows for the estimation of the human operator’s skeletal position and orientation in real-time, supporting process monitoring and efficient workspace utilisation. Additionally, the approach facilitates adaptable cobot responses based on the computed separation distances, providing an ideal balance between safety and efficiency of HRC tasks. The proposed FPSD framework is demonstrated to be viable in dynamic smart manufacturing environments (Choi et al., 2025).

3. Risk Assessment Methodologies: ISO 12100 defines risk as a blend of the severity of a hazard and its incidence probability. The proximity between human workers and cobots and a shared workspace means that mitigating risks by using risk and safety assessment [Atieh

Hanna et al., 2020] is imperative. The following methodologies were discussed in the studied papers:

a. Vicentini et al. suggest using “Safety Assessment through Formal Verification in HRC (SAFER-HRC)” for safety assessment in task execution. SAFER-HRC uses “model-based formal verification”, namely, to analyse all the possible ways of execution of the different tasks involved in the application of the HRC, to calculate the risk involved. SAFER-HRC supports the human risk assessor in this process by enhancing the accuracy and comprehensiveness of manual risk assessment and decreasing the effort needed for a rather complete safety assessment (Vicentini et al., 2020).

b. Lačević et al. (2013) present a safety assessment framework for HRC based on the concept of a “danger field”, a quantity that evaluates risk posed by the cobot to objects in its environment by considering the velocity of its motion and spatial configuration of its manipulators. The Kinetostatic Danger Field (KSDF) is a combination of the robot velocity and the relative angular position between the robot velocity and relative positions from a point where the danger field is calculated. The methodology is designed to pinpoint and resolve possible harmful situations using the KSDF. For instance, if the calculated danger is greater than a certain value, the current task is suspended and resumed when the danger conditions change to safe conditions. (Lačević et al., 2013).

c. Badguna et al. propose that a “virtual fencing framework” can be employed to ensure safe operation in HRC applications by predicting the movement of human workers. Protocols generally require HRC tasks to be suspended when a human enters a hazardous area within the operational zone, which results in increased downtime. However, the proposed methodology utilises “real-time ambient sensing”, enabling cobots to redefine risk zones based on the evolving environment and allowing for dynamic risk assessment. The virtual fencing framework aims to address the decreased productivity resulting from unpredictable human movement, while being experimentally proven to be cost-effective and adaptable to a variety of diverse industrial and collaborative applications (Badguna et al., 2025).

4. Human Factors and Ergonomics: In industrial HRC applications, ergonomic design of collaborative workspaces is crucial to ensure the well-being of human workers and optimise efficiency (Proia et al., 2023). Physical ergonomics must be considered to reduce injuries related to hazardous and repetitive tasks, while cognitive ergonomics is crucial for minimising mental stress and discomfort associated with humans sharing workspaces with cobots in HRC applications (Proia et al., 2023).

a. Physical ergonomics: Physical ergonomics focuses on reducing the biomechanical strain to improve the physical well-being of human operators and is becoming increasingly important due to a rise in work-related musculoskeletal disorders (WMSD) (Proia et al., 2023). In the studies reviewed, several solutions addressing physical ergonomics are proposed or reviewed. Solutions reviewed by Cardoso et al. focused on several methodologies for physical ergonomics: solutions assessing manual workstations to identify physical strain and then designing collaborative workstations to reduce WMSD risk, solutions relying on algorithm-based methods to assign collaborative tasks based on ergonomic considerations, and solutions focusing on ergonomic postures for human operators in real time (Cardoso et al., 2021) Proia et al, however, propose trajectory-planning of the end-effector of cobots to optimize the posture of the human operator, while ensuring the movement is completed in the fastest possible time. Their proposed methodology satisfies ISO SSM requirements for HRC applications and provides the “best compromise” for time efficiency of the task and physical ergonomics of human workers.

b. Cognitive ergonomics: Cognitive ergonomics is essential in HRC applications to minimise stress experienced by human operators in shared environments, to allow for effective collaboration and increased productivity. Cardoso et al. highlight the importance of the human operator's trust in the cobot system for overall system performance, as inappropriate trust in the robotic partner could lead to increased operator workload and lower performance efficiency. Among the many studies, methodologies and tools, Cardoso et al. also examine the tool "trust calibration" for cognitive ergonomics. The tool enables operators to develop a more accurate and realistic understanding of the strengths and

limitations of the cobots, thus allowing for more effective and efficient HRC.

IV. CONCLUSIONS:

This literature review examined key safety considerations in industrial cobot systems across five core domains: physical safety and collisions, safety regulations and standards, risk assessment methodologies, sensing technologies, and human factors and ergonomics. The reviewed papers underscore the critical role of ISO regulations, particularly ISO 12100, ISO 10218 and ISO/TS 15066, in establishing a foundation for safe HRC deployment. The review identifies trends in the application of sensors within safety systems and examines two frameworks that employ multi-modal sensing technologies, highlighting their effectiveness in improving both safety and productivity. In addition, the paper reviews three different risk assessment methodologies, each of which offers distinct advantages in balancing operational safety and efficiency. Furthermore, the importance of both physical and cognitive ergonomics has been reviewed, and results underscore the importance of the well-being of human operators in system productivity. Collectively, the reviewed studies demonstrate that the design of safe and efficient cobot systems demands a multidisciplinary approach that integrates regulatory compliance, real-time sensing, adaptive risk assessment, and human-centred design principles.

V. FUTURE SCOPE:

The main weakness of this review is that it was not systematic but used a narrative methodology. The method of selection of the literature was not a systematic review but instead used a search protocol that was not fully reproducible. This approach can also lead to selection bias in the review process and might have excluded relevant contributions. A further shortcoming is related to the wide range of reviews–five different domains. Because of the scope of a single review, there was a need to adopt a holistic approach, which limited the analysis of individual domains. Consequently, within each area, further topics of interest could not be explored in detail. Additionally, the number of domains reviewed consists of only five domains, and other crucial safety parameters of cobot applications in industry were not addressed. Other domains related to safety in HRC can still be good avenues for further research because HRC safety for human workers is a multifaceted and multidisciplinary issue that is still maturing.

VI. FUTURE RESEARCH DIRECTIONS:

Based on the gaps identified in this review, the following topics should be chosen as directions for future research: (1) standardisation of methodologies to validate the approaches for risk assessment in real industrial settings; (2) integration of AI and machine learning with formal safety verification; (3) comprehensive ergonomic studies that cover both physical and cognitive aspects of HRC; (4) analysis of safety-security interactions in connected cobot systems; and (5) longitudinal studies to evaluate the long-term safety effects of introducing cobots to industrial settings.

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