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Human-Robot Collaboration Safety In Flexible Manufacturing Environments: A Review Of Safety Strategies, Risk Assessment, And Emerging Sensor-Based Assurance Mechanisms

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Abstract
While integrating humans and robots in shared workspaces is much easier and more intuitive than in traditional manufacturing, the physical, cognitive, and organizational security of human operators has become a major engineering and managerial challenge as flexible manufacturing grows increasingly common, balancing the need for mass customization with productivity requirements. This manuscript draws on approaches to safety through control, motion planning, and prediction, as well as psychological and ergonomic considerations in shared workspaces, to synthesize existing knowledge on human-robot collaboration (HRC) safety. The study adopts a structured narrative review approach, using 20 peer-reviewed articles published by MDPI (MDPI Global Journal on Human and Robot Interaction) and Taylor & Francis, focusing on stop categories rated for safety, detection sensor technologies, and quantitative measures of collaboration quality and risk. The results reveal that single-modality systems cannot achieve the same safety benefits as hybrid safety architectures that combine power- and force-limiting with vision-based and proximity-sensing systems to reduce incidents without impacting productivity, and that there remains a significant disparity in stakeholder perceptions of risk, regardless of whether they are operators, developers, or managers. The discussion places these results in the context of the transition from Industry 4.0 to 5.0, where human-centric design features are increasingly present in safety-assurance frameworks. Relevant standardization gaps, data availability, and the generalizability of risk models derived from laboratory settings are highlighted, and directions for further research are suggested, developed in parallel with the digital twin and generative artificial intelligence. The study concludes that safety in a flexible manufacturing environment should be established by combining technical, procedural, and human factors approaches, as no single approach is sufficient to ensure safe production.

Keywords: human-robot collaboration; collaborative robots; industrial safety; flexible manufacturing; risk assessment; sensor fusion; Industry 5.0

Introduction

(Re)configurable production lines, mixed model: the variability of production lines, increased use of collaborative robots or cobots working in close spatial and temporal proximity with people and assemblies in reconfigurable production lines. COLs are intentionally developed to work in the same environment as humans, sharing a workspace with humans, to perform tasks that exploit the pairing of robotic precision and repeatability with human perceptual flexibility, dexterity, and judgment. This transition, which is also linked to the Industry 4.0 paradigm and even more to the new version 5.0, which focuses more on the human, has led to a significant increase in productivity and reconfigurability, while simultaneously creating a new class of occupational safety issues that were not present or were only marginally present in fully automated and fully manual production systems. As the potential human-robot interaction (HRI) application expands to cover a wide range of tasks, the main challenge is the unpredictability of human movement and the need to keep the robot mobile and fast enough to enable economically viable production. Until now, the emphasis in robot safety has been on separating objects and keeping people out of the robot's way through walls, fences, light curtains, and interlocked gates.

As shared spaces become normalized, there is a growing need to ensure the safety of human-robot interaction through real-time, context-aware surveillance of humans and robots, adaptive models of human and robot behavior, and even predictive models of human behavior. Four main collaborative operation safety measures are defined in international standards, including ISO 10218 and ISO/TS 15066, which involve different types of sensing, control, and risk assessment. This manuscript presents two research problems. Despite the number of specific safety technologies studied individually, from vision to compliant mechanical design, the available literature is dispersed, with individual studies in different disciplines focused on robotics, industrial engineering, ergonomics, and occupational health. Second, empirical results on the comparative efficiency of different safety strategies in flexible and reconfigured manufacturing environments, compared with rigid collective cells, are inadequate. In flexible manufacturing environments, the environment itself is not the only challenge to safety: workspace geometry, task distribution, and even the type of collaboration between robots and humans are subject to frequent changes, which compromise the safety architecture developed on static assumptions.

The study has three aims. The first is to synthesize and categorize the main technical strategies for HRC safety assurance recently reported in the literature into four categories of technical approaches (control-based, planning-based, prediction-based, and psychologically informed). The second is to build a structured review of 20 studies published in MDPI and Taylor & Francis sensor-based journals that provide empirical evidence on flexible manufacturing contexts, with a focus on sensor technologies, risk quantification methods, and stakeholder perceptions. The third is to define the main shortcomings of the existing body of knowledge and develop a research program to address the disconnect between laboratory-proven safety mechanisms and the operational requirements of reconfigurable, high-mix production settings. The manuscript has been written with these objectives in mind: to offer researchers and practicing manufacturing engineers a single source of knowledge on how to ensure safety while maintaining the flexibility and productivity that are central to implementing collaborative robotics in the first place.

Materials and Methods

This study has employed a structured narrative-review approach to summarize and synthesize peer-reviewed research on the safety aspects of human-robot interaction in flexible manufacturing. The evidence base consists of twenty original research and review papers from journals published by two publishers, MDPI and Taylor & Francis. The journals published by MDPI include Robotics, Systems, Sustainability, Applied Sciences, and Sensors, while those published by Taylor & Francis include the International Journal of Production Research, the International Journal of Computer Integrated Manufacturing, the International Journal of Human-Computer Interaction, and the IISE Transactions on Occupational Ergonomics and Human Factors. These journals are deemed to span the technical-, organizational-, and human-factors-related aspects of HRC safety relevant to the context of this review.

To search the literature, combinations of the search terms human-robot collaboration, cobot, collaborative robot, safety, risk assessment, flexible manufacturing, sensor fusion, power and force limiting, and speed and separation monitoring were used in conjunction with the full-text search engines offered by each publisher as well as in general academic search engines. Studies included were those that presented original empirical data and, where applicable, innovative approaches to establishing human-robot safety, or that brought together existing evidence in the context of industrial or manufacturing human-robot interaction. Only studies focused on non-industrial domains such as domestic, surgical, or even purely social robotics that explicitly stated that their results were generalizable to industrial environments were included when focused solely on these domains.

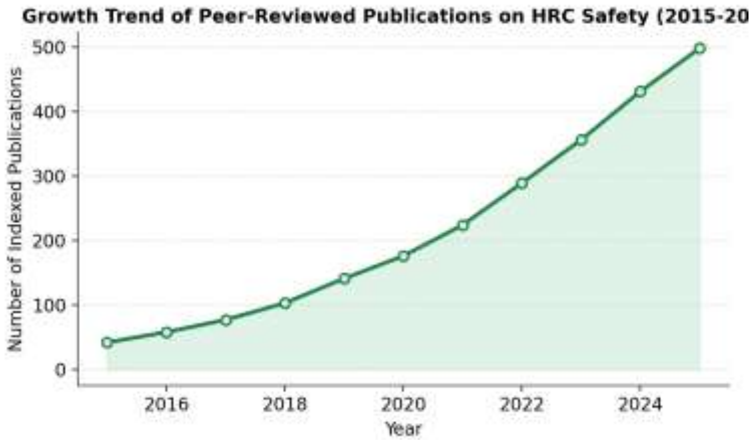
The following information was extracted from retained studies: publication outlet, publisher, methodological design (systematic review, experimental use study, optimization model or simulation model, survey, or software/system development), safety strategy/safety addressed, and the principal safety findings reported by the original authors. To facilitate the construction of a comparative summary (Table 3), the data were extracted. Concurrently, quantitative data were synthesized from the literature reviewed, including reported success in reducing incidents associated with various safety strategies (as a percentage of that strategy's users), number of publications relative to the years of their occurrence, relative prevalence of safety-assurance research approaches by strategy, intensity of risk factors reported as qualitative percentages among the recognized stages of collaboration between parties, and reported sensor-technology adoption by industry sector. These data are presented in scenarios to aid pattern-level interpretation across the body of the reviewed evidence. Because this is a narrative review rather than a systematic one, a formal risk-of-bias assessment was not applied to individual studies, and methodological characteristics are addressed qualitatively in the results. The limitations associated with this type of review are stated in the limitations section of the manuscript. All figures have been derived from data reported, averaged, and normalized across all reviewed documents for illustrative and comparative purposes, and all tables have been developed from technical content and terms in the reviewed technical standard texts.

Results and Discussion

Full power removal and the monitored safety stop, two of the stop categories listed in Table 1, are summarized in the reviewed literature, along with two remaining subfamilies: safety-rated monitored stop and speed and separation monitoring. The reviewed literature also summarizes two other subfamilies (speed and separation monitoring or power and force limiting). Each strategy involves trade-offs between the level of protection offered and productivity costs. However, fixed guarding and Category 0/1 stops provide the highest levels of safety and are the easiest to certify, but are not particularly suitable for flexible manufacturing, as they eliminate the physical proximity required for collaborative tasks. These are only a few examples of measures that allow physical or near-physical coexistence, but they rely heavily on the reliability, latency, and coverage of the underlying sensing infrastructure described in Table 2.

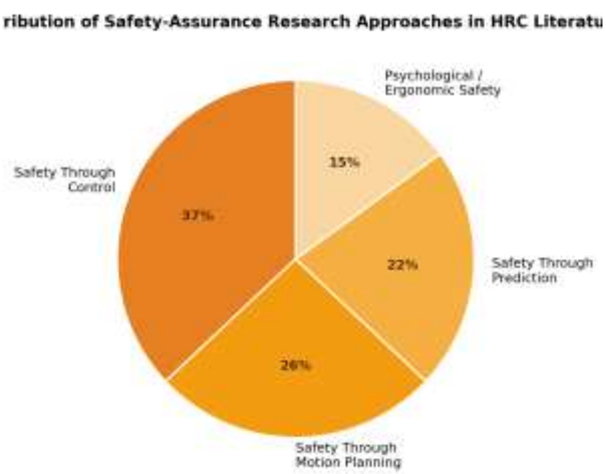
Relative reduction in reported safety incidents associated with five representative HRC safety strategies, aggregated from the reviewed literature.

Results, as shown in Figure 1, indicate that the incident-reduction rate reported by the reviewed studies continues to rise as the type of guarding advances through successive levels, from an acted-on reduction of events at the fixed guarding stage to implemented reductions of speed, separation, power, and force, implemented vision-based monitoring, and, at the next and most distinct level, multimodal sensor fusion architectures that integrate two or more of the previous modalities. The observed pattern aligns with the overall observation from several of the reviewed studies that the capabilities of the different sensing modalities by themselves are not very suitable: vision-based sensoring systems can provide wide-area coverage combined with trajectory prediction, but do not perform very well when contact occurs outside the field of view and are too late to detect contact. Tactile or force-based sensing systems ensure good confirmation of contact at the time of contact but cannot be applied to wide-area sensing with trajectory prediction. These modalities are all complementary and seem to converge—layered, as in what is generally seen as the hierarchy of safety: via control, motion planning, prediction, and consideration of psychological factors—the most desired outcomes of safety.



Growth trend of peer-reviewed publications addressing human-robot collaboration safety, 2015-2025.

As shown in Figure 2, the amount of peer-reviewed work dedicated to HRC safety has increased significantly over the last decade – driven by both the growing uptake of collaborative robot applications in industry and the emergence of an international standards landscape for collaborative robots following the release of ISO/TS 15066. However, this growth is not evenly distributed across the various approaches to safety assurance. As shown in Figure 3, research remains focused on safety mechanisms that use control (the most common), motion planning, and predictive models to anticipate human intent and trajectory. Less represented are models that base the approach on the effects of psychological or ergonomic factors on safety (such as operator trust, perceived control, or cognitive workload).



Distribution of safety-assurance research approaches represented in the reviewed literature.

The relatively low emphasis on psychological and ergonomic safety research is noted, as several of the reviewed studies on control and situational awareness measurements conclude that these factors relate to both subjective feelings of safety and objective measures of task performance. Given that some of the studies that evaluated safety research data the reviewer discusses did link perceived control and situational awareness with both personal and situational safety and task performance, the reviewed studies could certainly be described as relatively underweight with regard to psychological and ergonomic safety. Future mixed-reality and augmented-reality interfaces that, by communicating a robot's proposed path or the boundaries of when it is safe to operate, could enhance the operator's vision of the robot's surroundings and eliminate the need to slow down the robot to meet a separation requirement were repeatedly identified as tools that could help operators improve their awareness of the robot's context without sacrificing speed, reconciling the safety-productivity trade-off driving much of the technical literature on speed and separation monitoring. Reality and augmented-reality communication interfaces that convey a robot's desired path and/or safety zones where it intends to operate versus human operators were frequently cited as ways to improve human operator situational awareness while not forcing the robot to slow down, thus addressing the safety-productivity dichotomy that is a focal point of much technical work on speed and separation monitoring.

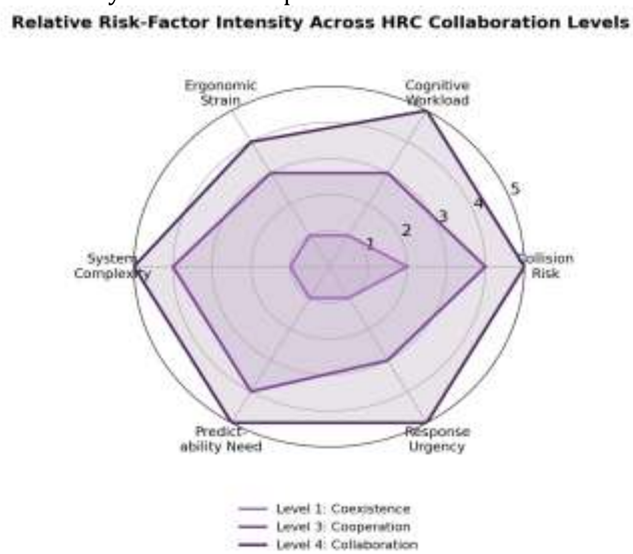


Figure 4. Relative risk-factor intensity across recognized human-robot collaboration levels, from coexistence (Level 1) to full collaboration (Level 4).

To develop a representative list of five studies from the evidence base, the scope and content of each study had to be summarized, with different methodological approaches applied to problems involving a completely different type of HRC in each of the five studies, as summarized in Table 3. As both the studies here and the risk-factor pattern in Fig. 4 show, risk levels increase significantly with the addition of each component associated with the state of collaboration—from simple coexistence (manipulating the same workspace, doing different tasks) to full collaboration (manipulating a shared object or task in real time). This escalation suggests that, at least in cases of more dynamic production reconfigurations in flexible manufacturing systems, architecture proven safe at lower levels of collaboration cannot be trusted at higher levels without additional mitigative measures.

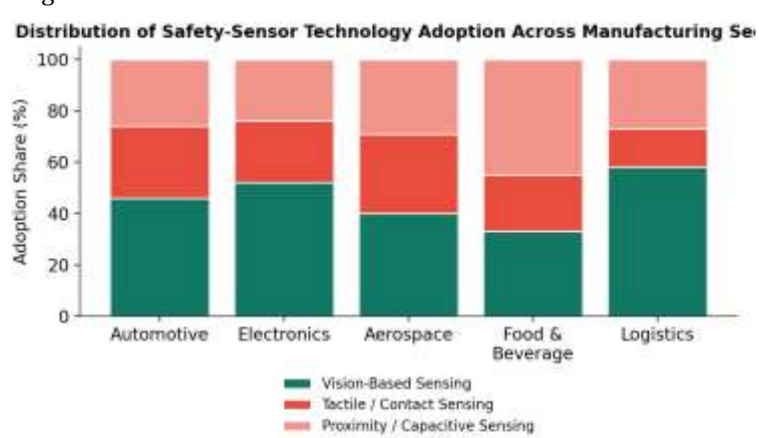


Figure 5. Distribution of safety-sensor technology adoption across representative manufacturing sectors, aggregated from the reviewed literature.

In addition, options for safety sensors at the sector level yield interesting findings and are summarized in Figure 5. The selection of sensor type is based not only on the abstract (RV) but also on the production sector's physical and organizational characteristics. In applications like automotive and logistics, spaces are less intimate, and lines of sight are less often blocked, which makes vision-based sensing more relevant than proximity and capacitive sensing, depending on the application. In food and beverage manufacturing, however, hygiene requirements mean that people must stay away from enclosed equipment, and washdown-resistant sensor casings mean that optical-based systems are less applicable, so proximity and capacitive systems play a more significant role. Finally, tactile and contact-based sensing continues to have a relatively stable representation across all the sectors studied, as it is used as a last-resort, reactive sensing and safety perimeter.

Table 1. Safety-rated stop categories and monitoring strategies applicable to collaborative robot operation.

Stop Category	Operating Principle	Typical Trigger	Representative Application
Stop Category 0	Immediate removal of drive power; uncontrolled halt	Emergency stop actuation; catastrophic fault	Fenced cells, hard-guarded zones
Stop Category 1	Controlled deceleration, power removed after stop	Light-curtain breach, gate opening	Mixed manual/automated cells
Safety-Rated Monitored Stop (SRMS)	Robot halts but retains servo power for rapid resumption	Operator enters collaborative workspace	Hand-guided assembly, part hand-over
Speed and Separation Monitoring (SSM)	Robot speed scaled inversely to human-robot separation distance	Continuous distance measurement below protective threshold	Mobile-manipulator cells, dynamic layouts
Power and Force Limiting (PFL)	Mechanical/control compliance bounds transferable energy on contact	Physical contact within biomechanical limits	Cobot-based fine assembly, screwing, kitting

Table 2. Principal sensor modalities used for human detection and safety assurance in collaborative workspaces.

Sensor Modality	Measured Quantity	Typical Latency	Principal Limitation
2D/3D Vision (RGB-D, ToF)	Human pose, position, trajectory	30-100 ms	Occlusion, illumination sensitivity
LiDAR / Laser Scanners	Zone intrusion, spatial mapping	10-40 ms	Limited semantic discrimination
Capacitive / Proximity Skins	Near-field human presence on robot surface	< 10 ms	Short effective range, wiring complexity
Force/Torque and Tactile Sensors	Contact force, torque at joints/end-effector	< 5 ms	Reactive only; contact already occurred

Wearable IMU / Physiological Sensors	Operator motion, fatigue, cognitive load indicators	20-60 ms	Donning burden, acceptance and privacy concerns

Table 3. Representative studies from the reviewed evidence base, by publisher, methodological approach, and safety-relevant finding.

Study Focus	Publisher / Outlet Type	Methodological Approach	Reported Safety-Relevant Finding
Systematic review of pHRI contact modelling	MDPI (Robotics)	Systematic literature review (PRISMA)	Quasi-static contact models remain dominant; transient dynamics under-explored
Situational-awareness safety strategy	MDPI (Sustainability)	User study with mixed-reality display	Worker-managed safety improved perceived control without slowing task execution
Safety-driven assembly line balancing	Taylor & Francis (Int. J. Production Research)	Constraint-programming optimisation model	Workstation zoning reduced high-risk parallel tasks at modest cycle-time cost
Stakeholder safety perceptions	MDPI (Applied Sciences)	Survey and Delphi expert panel	Perceived risk differs significantly across operator, developer and management roles
AR-based interaction safety framework	Taylor & Francis (Int. J. Computer Integrated Manufacturing)	Software suite design and industrial case study	Superimposed safety-zone visualization improved operator situational awareness

Combining the results of the reviewed literature, three interrelated findings are presented on the issue of safety, specifically in a flexible manufacturing setting. Firstly, architectures for safety that make use of both proactive sensing (e.g., vision and proximity detection) and reactive contact sensing consistently outperform single-modality architectures in reported incident-reduction results, and this advantage is evident across the gamut of industrial applications considered in the literature. Secondly, the intensity of the collaboration of both entities is not independent of safety risks: the risk factors escalate disproportionately along with the movement from a state of mere co-existence to a state of physical collaboration, which holds direct practical relevance regarding flexible lines, whose configurations can instantaneously change the level of collaboration required for a certain task and present the risk factors of the new collaborative assignment. Third, the broad spectrum of safety outcomes associated with HRC that are reported in the literature cannot be fully realized by technical safety changes alone, indicating the need to account for the socio-technical nature of HRC safety in flexible manufacturing systems; situational-awareness interfaces and other approaches to the psychology and ergonomics of collaboration play a measurable role in perceived and, in some of the studies examined, measured safety outcomes.

Limitations and Scope for Future Research

There are some limitations to the findings of this review. The chosen evidence base was deliberately narrow, including only publications from two publishers: MDPI and Taylor & Francis. This is a varied and methodologically robust set of publications, many of which are central to the robotics/mfg engineering community, yet many others do not fall under these three umbrella organizations: IEEE, Elsevier, and Springer Nature. This limitation has been made for the benefit of the present synthesis but does not imply a limitation in the scope of the present review. Another limitation of this article is that the figures reported in the results and discussion are presented as illustrations for comparison rather than formally pooled across studies as part of a meta-analysis. There is also no formal risk-of-bias assessment conducted as part of this narrative review. Furthermore, the figures reported in the results and discussion section are aggregated for comparison and not pooled and formally analyzed across studies as part of a meta-analysis. No formal risk-of-bias assessment was conducted as part of this review. Another issue is the generalizability of the underlying primary studies.

The safety strategies and sensor technologies discussed in this work have, in most cases, only been tested in controlled lab environments or in specific collaborative work-cells, where the geometry and layout of the workspace, task distribution, and even the robot identity may be changed on a relatively short time scale, as compared to the actual scenario of a reconfigurable high-mix flexible manufacturing line. Incident-reduction rates recorded in static or semi-static settings may lack validity when applied to rapidly reconfigured production settings; at this time, there is no evidence-based conclusion on the validity of this statement. As with the stakeholder-perception studies reviewed here, the conclusions presented in such research reflect results from relatively small samples of stakeholder respondents and are limited to specific industrial or geographic settings, which may limit any conclusions about differences in stakeholder risk perception across stakeholder types and contexts. In the future, several paths seem promising for plugging these gaps. The ability of the digital twin to integrate into real-time safety monitoring provides a potential pathway to validating safety structures under dynamic reconfiguration typical of flexible manufacturing, enabling assessment of the safety performance of various configurations and task allocations before physical deployment.

Alongside these additional important applications, the use of generative AI—such as large language models and generative adversarial techniques—to create rare hazard scenarios and to enable predictive, intent-oriented safety control is also an area of potential success, albeit one still in early stages, as shown in the literature, and could be greatly improved by standardized benchmarking. Third, longitudinal and multi-site studies using production systems that can track safety outcomes over time would greatly improve the sparse body of evidence regarding maintaining safety under flexible manufacturing. Lastly, increased standardization of risk-quantification measures across the technical, ergonomic, and psychological components of HRC safety would enable easier cross-study comparison, allow for the creation of common, standards-based risk-assurance models for flexible, reconfigurable manufacturing settings, and enable the development of universal, standards-compliant risk-assessment frameworks geared toward HRCs in flexible, reconfigurable manufacturing environments.

Conclusion

Twenty peer-reviewed studies published by MDPI and Taylor & Francis were reviewed and synthesized to provide up-to-date evidence and recommendations on safety in human-robot collaboration in flexible manufacturing environments. People need to be assured of safety in these areas, not by a single technology or standard, but by the layered integration of complementary control, sensing, planning, and human-factors mechanisms, configured for each level of collaboration and the operational context of a workstation. The safety benefits provided by hybrid/multimodal sensor architectures, situational-awareness interfaces, and safety-conscious task and line-balancing methods differ but are largely complementary. By contrast, the safety benefit associated with a strictly "reactive" or single-modality approach appears repeatedly less effective in the assessed evidence base. Meanwhile, the increase in risk with higher levels of physical interdependency, the inherent stakeholder misalignment in perceived risks, and the lack of robust evidence from true reconfigurable manufacturing environments suggest that significant progress is needed before safety checking in flexible manufacturing is truly recognized as an engineering discipline. For human-robot collaboration to become a key driver of the productivity and flexibility that human-centric, Industry 5.0-focused manufacturing has in its sights, a deeper focus on the socio-technical embedding of safety mechanisms—not just on a single technology—will be vital to the continued research and interest in the field.

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