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# Human-Centered Robotics for Safer Collaborative Manufacturing

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**Abstract**

Collaborative robotics is transforming manufacturing by enabling human operators and robotic systems to perform interdependent tasks within shared production environments. Unlike conventional industrial automation, where physical barriers traditionally separate workers from robot motion, collaborative manufacturing requires safety to be managed continuously through robot design, system integration, sensing, task allocation, interaction logic, ergonomics, training, and organizational controls. This paper develops a human-centered framework for safer collaborative manufacturing in which physical safety is treated as necessary but insufficient for effective human–robot collaboration. The proposed approach incorporates mechanical risk reduction, speed and separation management, power and force limitation, cognitive ergonomics, workload-aware task allocation, explainable robot behavior, operator control, trust calibration, and continuous safety monitoring.

Because no real manufacturing dataset was provided, the quantitative component is explicitly presented as a simulation-based methodological analysis. Four hypothetical workstation configurations are evaluated: fenced automation, a basic collaborative cell, a safety-optimized collaborative robot cell, and a human-centered adaptive human–robot collaboration system. Five performance dimensions are considered: physical safety, ergonomic quality, operator situation awareness, calibrated trust and acceptance, and collaborative task performance.

The simulated composite safe-collaboration score increases from 52 in fenced automation to 68 in basic collaboration, 81 in the safety-optimized configuration, and 91 in the human-centered adaptive system. These results are illustrative rather than empirical. The study argues that safer collaborative manufacturing requires an integrated sociotechnical design approach in which robot safety standards are complemented by human-factors engineering, adaptive work allocation, clear communication, worker participation, and continuous validation. The resulting Human-Centered Collaborative Robotics Safety Framework provides a structured foundation for future factory experiments and industrial deployment.

***Keywords:*** human-centered robotics; collaborative manufacturing; collaborative robots; human–robot collaboration; industrial safety; cognitive ergonomics; robot trust; task allocation; Industry 5.0; manufacturing ergonomics

## 1. Introduction

Industrial robotics has traditionally been associated with highly automated production environments in which robots perform repetitive, high-speed, or hazardous tasks inside physically separated work cells. Conventional safeguarding strategies reduce human exposure primarily by restricting access to the robot operating area. Collaborative robotics changes this operating principle by allowing certain industrial robot applications to function in direct interaction with workers under carefully controlled conditions.

The current international safety framework reflects this transition. ISO 10218-1:2025 specifies safety requirements for industrial robots themselves, including inherently safe design and risk-reduction measures, whereas ISO 10218-2:2025 addresses the integration, commissioning, operation, maintenance, and decommissioning of complete industrial robot applications and robot cells. ISO/TS 15066:2016 supplements the industrial robot standards with requirements and guidance specifically relevant to collaborative robot applications.

Collaborative applications create major opportunities for manufacturing because humans and robots possess complementary capabilities. Robots can provide repeatability, precision, sustained force, consistent movement, and assistance with physically demanding activities. Humans provide adaptability, contextual reasoning, dexterity in unstructured situations, rapid response to unexpected events, and flexible problem solving.

This distinction is important because a robot marketed as collaborative does not automatically create a safe collaborative application. OSHA guidance similarly distinguishes collaborative applications according to the way workers directly interact with robot systems and emphasizes risk assessment, risk-reduction measures, training, safeguarding, and evaluation of the complete application.

Workers may experience physical fatigue, awkward posture, excessive monitoring demands, uncertainty about robot intentions, cognitive overload, loss of perceived control, inappropriate trust, or frustration with poorly coordinated robot actions. Experimental research on collaborative assembly has shown that workstation features and interaction conditions can affect cognitive workload, usability,.

Human-centered robotics therefore requires the design team to address both what the robot is technically capable of doing and what the human operator experiences while working with it.

## 2. From Industrial Automation to Human–Robot Collaboration

Traditional automation has frequently been designed around separation. Industrial robots can execute movements with high speed, payload, and repeatability, but their motion can create crushing, impact, trapping, cutting, and other hazards when people unexpectedly enter the operating area.

Collaborative manufacturing introduces a different configuration.

**The worker and robot may share:**

- the same workstation,
- the same product,
- the same task sequence,

or portions of the same operating space.

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## 3. Physical Safety in Collaborative Robotics

### 3.1 Risk Assessment as the Starting Point

Collaborative manufacturing should begin with task-specific risk assessment.
A valid assessment examines the complete application, including:

- robot motion;
- tooling;
- workpieces;
- fixtures;
- sharp edges;
- payload;
- human access;
- unexpected start-up;
- energy sources;
- process hazards;
- maintenance;
- foreseeable misuse;

and possible failure conditions.

### 3.2 Safety-Rated Monitored Stop

A safety-rated monitored stop can halt robot motion when a person enters a defined collaborative space while maintaining controlled system status.

This method can provide a straightforward safety concept where simultaneous human and robot motion is unnecessary.

Frequent stopping and restarting may reduce collaborative fluency when workers repeatedly enter the robot workspace.

### 3.3 Speed and Separation Monitoring

Speed and separation monitoring manages robot motion according to the distance between humans and hazardous robot elements.

The robot may operate normally while sufficient separation exists, slow when a worker approaches, and stop when the protective separation requirement can no longer be maintained.
Vision, laser scanners, depth cameras, and other sensing technologies can support such approaches.
Vur, Petzoldt, and Freitag experimentally compared collaborative safety strategies using a top-view RGB-D camera system in an assembly scenario with 12 participants. Their results showed that enhanced safety strategies could improve acceptance and interaction fluency, although execution time could increase.

## 4. Why Physical Safety Alone Is Not Human-Centered Safety

A technically compliant workstation may still create undesirable working conditions.

Consider an operator who knows that the robot will stop before collision but cannot predict when it will move.

Gualtieri and colleagues experimentally evaluated cognitive-ergonomics guidelines in collaborative assembly and found that progressive improvement of workstation and interaction conditions improved participants' cognitive responses and assembly performance.

Human factors should therefore be incorporated during workstation design rather than evaluated only after robotic hardware has already been installed.

## 5. Ergonomics in Collaborative Manufacturing

### 5.1 Physical Ergonomics

One of the strongest potential advantages of collaborative robotics is the opportunity to transfer physically demanding components of work from humans to robots.

Examples include repeated lifting, holding heavy parts, sustained awkward postures, high-force fastening, and repetitive motions.

If the robot receives all physically demanding but cognitively simple tasks while the worker repeatedly performs fine manipulation at an awkward workstation, musculoskeletal risk may remain.

The collaborative cell should therefore be designed around the complete human movement pattern.

### 5.2 Dynamic Ergonomic Task Allocation

Static allocation assigns tasks before production begins.

Dynamic allocation allows responsibilities to change according to system conditions.

Merlo and colleagues developed an ergonomic role-allocation framework that incorporated changing human physical risk into task assignment. In multi-participant experiments, the framework recognized high-risk actions and redirected them away from human operators, with reported reductions in fatigue and frustration.

### 5.3 Human Well-Being in Industrial Applications

Evidence from real manufacturing applications further supports worker-centered adaptation.

Montini and colleagues reported an industrial collaborative cell in which assembly and screwdriving were coordinated by a system considering production conditions together with perceived physical fatigue and hand preference. Their industrial case reported improved workload balance, lower perceived fatigue, higher job satisfaction, and shorter cycle times.

This finding is important because human-centered design does not necessarily require sacrificing productivity.

## 6. Cognitive Ergonomics and Situation Awareness

Collaborative robots are moving machines with autonomous or semi-autonomous behavior.

Workers must understand enough about robot state and intention to interact safely.

**Questions naturally arise:**

- Is the robot about to move?

- Which component will it collect?
- Has it detected the worker?
- Why has it slowed?
- Is it waiting for assistance?

Workers may repeatedly monitor the robot rather than focus on their own task.

**7. Trust and Appropriate Reliance**

Trust is essential in collaborative manufacturing because operators must decide when they can rely on robotic behavior.

Charalambous, Fletcher, and Webb developed an industrial human–robot collaboration trust scale, demonstrating that trust can be treated as a measurable human factor rather than an informal impression.

Recent experimental work has also investigated objective signals associated with trust. Campagna, Chrysostomou, and Rehm used facial-feature analysis during an industrial collaborative scenario to examine trust evaluation in human–robot interaction.

**8. Human Authority and Operator Control**

Collaborative systems should preserve appropriate human authority.

**Workers require a clear understanding of:**

- how to stop the system;
- how to request assistance;
- how to recover from errors;
- how to reject an automated decision;

and how to place the system in a safe state.

**9. Human-Centered Task Allocation**

Task allocation is central to collaborative manufacturing.

An effective system should allocate work according to the strengths, limitations, and current state of each resource.

Michalos and colleagues developed a multi-criteria method for planning shared human–robot tasks that jointly considered ergonomics, productivity, technical feasibility, quality, and workstation layout. The method was validated using an automotive assembly case.

Petzoldt and colleagues later investigated dynamic task allocation in collaborative assembly and reported improved collaborative fluency and reduced cycle time under suitable task conditions.

These studies suggest that task assignment should not be based only on the question of which agent can perform an activity fastest.

**10. Research Gap**

Despite rapid progress in collaborative manufacturing, several gaps remain.

First, safety engineering and human-factors engineering are still frequently treated as separate activities.

Robot safety may be validated technically, while ergonomics and worker acceptance are studied later. Second, many systems optimize productivity and collision avoidance but do not simultaneously evaluate cognitive workload, trust, perceived control, fatigue, and operator experience.

The long-term effects of collaborative robotics on worker well-being, skill utilization, and trust require continued evaluation.

**11. Novelty and Proposed Contribution**

1. The paper proposes the Human-Centered Collaborative Robotics Safety Framework (HCRSF).
2. The framework evaluates collaborative manufacturing through six interconnected principles.
3. Physical Safety: robot and application-level risk must be reduced using appropriate technical and organizational measures.
4. Ergonomic Safety: work allocation should reduce physical strain and avoid transferring risk between tasks.
5. Cognitive Safety: robot behavior and interfaces should limit unnecessary workload, uncertainty, and monitoring demand.
6. Calibrated Trust: workers should understand both the robot's capabilities and its limitations.

The central contribution is to treat collaborative manufacturing as a sociotechnical safety system rather than a robot-safety problem alone.

**12. Research Objectives**

The study aims to evaluate how increasingly human-centered design principles could affect collaborative manufacturing safety and performance.

**The specific objectives are:**

1. To compare conventional and collaborative manufacturing configurations across physical and human-centered safety dimensions.
2. To examine the role of ergonomics, workload, situation awareness, and trust in collaborative robot design.
3. To evaluate the potential benefit of adaptive human-aware task allocation.
4. To develop a composite safe-collaboration evaluation approach.
5. To propose practical requirements for safer human-centered collaborative manufacturing.

**13. Research Questions**

- Does collaborative robot integration automatically produce safer manufacturing than conventional automation?
- How do cognitive and physical ergonomics affect overall collaborative safety?
- Can adaptive task allocation improve operator well-being without reducing manufacturing performance?
- How do situation awareness and calibrated trust influence effective human–robot collaboration?
- Which characteristics distinguish a merely safety-compliant collaborative cell from a genuinely human-centered collaborative manufacturing system?

## 14. Methodology

### 14.1 Research Design

The study uses a simulation-based comparative research design.

No actual manufacturing workers participated in the present quantitative analysis.

The numerical results are synthetic and are included to demonstrate how the proposed human-centered framework could be empirically tested.

Four hypothetical workstation configurations were defined.

**Table 1: Simulated Collaborative Manufacturing Configurations**

| Configuration | Safety Architecture | Human-Factors Design | Task Allocation | Expected Human Role |
|---|---|---|---|---|
| C1: Fenced Automation | Physical separation and conventional safeguarding | Limited | Fixed | Loading, supervision and intervention |
| C2: Basic Collaborative Cell | Integrated collaborative robot safety functions | Basic interface and training | Predetermined | Direct workspace interaction |
| C3: Safety-Optimized Cobot Cell | Risk-assessed collaborative operation with enhanced monitoring | Improved ergonomics and state information | Semi-dynamic | Coordinated human–robot teamwork |
| C4: Human-Centered Adaptive HRC | Layered technical safety, human-aware monitoring and validated risk controls | Ergonomic, cognitive and participatory design | Dynamic and worker-aware | Flexible collaborative partnership |

### 14.2 Evaluation Dimensions

Five evaluation dimensions were modeled on a normalized scale.

- Physical Safety represented risk reduction, protective responses, monitored interaction, and safety-system robustness.
- Ergonomic Quality represented physical workload, posture, repetition, fatigue, and allocation of physically demanding activities.
- Situation Awareness represented the worker's ability to understand robot state, intention, and expected movement.

- Trust and Acceptance represented appropriate confidence, predictability, usability, and perceived control.

### 14.3 Composite Safe-Collaboration Score

**The simulated Composite Safe-Collaboration Score was calculated as:**

**[ SCS = 0.30P + 0.20E + 0.20A + 0.15T + 0.15C ]**

**where:**

(P) = Physical Safety
(E) = Ergonomic Quality
(A) = Situation Awareness
(T) = Trust and Acceptance
(C) = Collaborative Performance

Physical safety receives the highest weighting because no productivity benefit can justify an inadequately controlled safety risk.

The weights are methodological assumptions and are not presented as validated universal safety coefficients.

### 14.4 Proposed Questionnaire

The following five questionnaire items are proposed for future empirical validation and were not administered in the current simulation.

1. I can clearly understand what the robot is doing and what action it is likely to perform next.
2. I feel that the collaborative workstation allows me to work without unnecessary physical strain.
3. I trust the robot to behave consistently within the operating conditions I have been trained to understand.
4. I can easily stop, pause, or request a change in robot behavior when necessary.
5. The division of work between me and the robot helps me perform the task safely and effectively.

A future study may use a seven-point scale from 1 = strongly disagree to 7 = strongly agree.

## 15. Results

**Table 2: Simulated Performance Across Collaborative Workstation Designs**

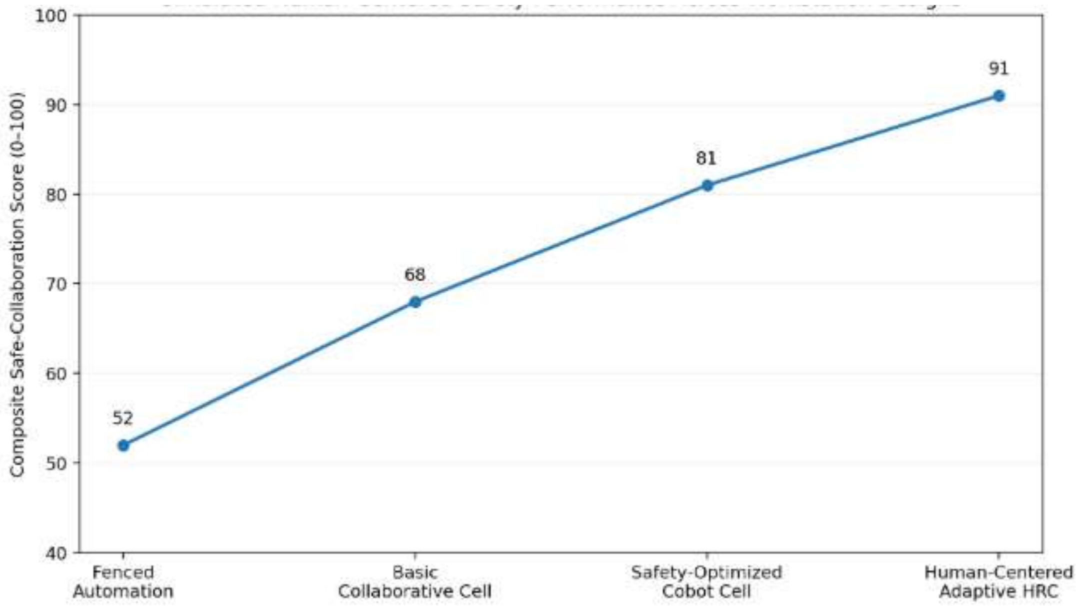
| Evaluation Dimension | Fenced Automation | Basic Collaborative Cell | Safety-Optimized Cobot | Human-Centered Adaptive HRC |
|---|---|---|---|---|
| Physical Safety | 83 | 73 | 91 | 96 |
| Ergonomic Quality | 45 | 67 | 82 | 94 |
| Situation | 38 | 61 | 83 | 93 |

| **Evaluation Dimension** | **Fenced Automation** | **Basic Collaborative Cell** | **Safety-Optimized Cobot** | **Human-Centered Adaptive HRC** |
|---|---|---|---|---|
| Awareness | | | | |
| Trust and Acceptance | 42 | 66 | 80 | 90 |
| Collaborative Performance | 52 | 72 | 84 | 91 |
| **Composite Safe-Collaboration Score** | **52** | **68** | **81** | **91** |

**Note:** All values are synthetic and should not be interpreted as measured accident, ergonomic, trust, or production data.

## 16. Graphical Analysis

**Graph 1: Simulated Human-Centered Safety Performance Across Workstation Designs**



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## 17. Discussion

### 17.1 A Collaborative Robot Is Not Automatically a Safe Application

The first implication concerns terminology.

- The presence of a collaborative robot does not eliminate the requirement for system-level risk assessment.
- The complete robot application—including tooling, workpiece, environment, operator access, control logic, and process hazards—determines the actual risk profile.
- This principle is directly consistent with the separation between robot-level requirements in ISO 10218-1:2025 and application/integration requirements in ISO 10218-2:2025.

### 17.2 Safety and Productivity Should Not Be Treated as Opposites

Collaborative safety mechanisms can affect cycle time.

1. The RGB-D monitoring study by Vur and colleagues found that safety strategies could improve acceptance and collaboration fluency while also increasing execution time.
2. This does not imply that safety reduces productivity.
3. An unsafe high-speed cell is not a viable productivity benchmark.
4. Manufacturing performance should instead be optimized within validated safety constraints.

More sophisticated sensing, planning, and human-aware control can then improve productive use of the remaining operating space.

## 18. Conclusion

Human-centered robotics offers an important pathway toward safer and more flexible collaborative manufacturing, but the presence of a collaborative robot alone does not guarantee a safe or desirable workplace.

Industrial safety standards provide the essential technical foundation. ISO 10218-1:2025 addresses safety requirements for industrial robots, while ISO 10218-2:2025 addresses complete industrial robot applications and cells. ISO/TS 15066 continues to provide complementary guidance for collaborative robot applications.

hile also reducing ergonomic strain, preserving situation awareness, supporting calibrated trust, communicating robot intentions, allowing meaningful operator control, and adapting task allocation to human capabilities.

The Composite Safe-Collaboration Score increases from 52 in the fenced automation scenario to 68 in the basic collaborative system, 81 in the safety-optimized collaborative cell, and 91 in the human-centered adaptive configuration.

The safest collaborative manufacturing system is not simply the robot that can work closest to a person. It is the complete work system that allows humans and robots to cooperate while physical risk, ergonomic burden, cognitive demand, uncertainty, and loss of control remain systematically managed.

Human-centered robotics should consequently be understood as the integration of safety engineering, robotics, ergonomics, human factors, manufacturing design, and worker participation.

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