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Safety Evaluation in Human-Robot Collaboration Through Risk Assessment Matrix and Observational Measurements

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Abstract
Manufacturing assembly activities are competing to be one of the most intriguing and promising applications in collaborative settings, accounting for about half of the typical workload in the real manufacturing process. Collaborative robots, or cobots, allow to enhance productivity and wellbeing in those manufacturing repetitive and tedious tasks. Hence, human robot-collaboration, named also HRC, activities have been recognized as one of the pivotal solutions to increase efficiency. However, safety considerations must be considered in the design of collaborative workplaces, where humans work alongside robots, as hazards arise. This paper highlights the design and implementation of a risk assessment matrix deployed for the implementation assessment of a cobot in a collaborative workplace. Two scenarios are defined in the modular assembly workstation set up in a laboratory environment: standard scenario – where participants accomplished an assembly task without any intervention - and collaborative scenario – where participants accomplished the same task working alongside the cobot. The cobot deployed for the collaborative activity is the industrial Melfa Assista Mitsubishi cobot, equipped with safety sensors and designed for collaborative tasks. Moreover, the choice of the gripper, the VGC10 Vacuum Gripper was crucial in the design of the collaborative task, considering safety aspects though. Finally, authors analyzed the productivity index through observational measurement and the quality of the task through questionnaires asked at the end of the tests to participants to further evaluate the level of efficiency of the task with the robot. Results showed a consinstent and significant increase of productivity in the collaborative scenario, highlighted by the statistical T-test analysis.

1 INTRODUCTION

The Industrial Revolution X.0 (IRX.0) referred to a series of substantial developments in manufacturing, technology, and society that occurred between the 18th and the present. These industrial revolutions had a tremendous impact on economies, cultures, and daily life, resulting in enormous shifts in work patterns, urbanisation, global trade, and technological advancement.

The most recent Industrial Revolution 4.0 (early 2000s - continuing), also known as IR4.0, addressed the challenge of human-centricity, sustainable development, and adaptability by emphasising outcomes and a defined technology plan. It entailed the incorporation of artificial intelligence (AI), machine learning (ML), robots, nanotechnology, biotechnology, and the internet of things (IoT) into the digital growth of the previous industrial revolution. Industry 4.0 brought a new level of interconnectedness, data-driven decision-making, and the integration of cyber-physical systems [1].

Amongst these recent innovations, collaborating robots, or co-bots, have enabled increased productivity and adaptation in industrial production processes [2,3]. Unlike traditional industrial robots, the introduction of cobots represents a larger movement in the area towards more interactive, flexible, and adaptable systems. This method is consistent with the IR4.0 principles of bridging automation, data interchange, and human-machine cooperation

(HRC) in industrial settings [4,5]. HRC has enabled enhanced adaptability manufacturing processes that can respond fast to changes in product design, production numbers, or customisations without requiring extensive reprogramming or reconfiguration. Thus, the change from a manual to a human-robot collaborative activity may result in a decrease in takt time since cobots may perform some tasks faster than humans, thereby enhancing productivity. Furthermore, cobots' efficiency and reproducibility can reduce the number of defective items produced by human error [6].

However, these novel devices, outfitted with sophisticated sensors, could be used in fenceless environments where mechanical hazards are the primary concern. Common mechanical hazards include crushing, shearing, cutting, tangling, trapping, impact, stabbing, and abrasion. Nonetheless, hazard situations such as entrapment between robot system components and the workplace (e.g., equipment, fixtures, guards), trapping between parts of the robotic system itself (cables, manipulator, end-effector, etc.), unexpected or unwanted contact with moving parts, effects related to the loss of the workpiece during handling and processing, and effects related to the specific loss (screwing, glueing, etc.) can be hazardous. These considerations influence both the operator's and the system's safety [7].

Based on such circumstances, the official guidelines [8,9] suggest four safe types of contact between operators and robots. Various authors utilise a variety of these modes. A discrete-event controller, as proposed by Heinzmann and Zelinsky [10], is a mode that remains active throughout collaborative activities. Long et al. [11] describe a distance-triggered system that switches between nominal (maximum velocity), reduced (speed limiting), and passive (hand-guided) operational modes. Kaiser et al. [12] and Villani et al. [13] identify and incorporate these modes into workplace arrangements. The International Federation of Robotics [14] described various levels of collaboration between an operator and a cobot, each defined by the level of involvement and the type of activities done. The mode of operation is decided by variables such as task complexity, safety concerns, required precision, and desired level of human engagement. As cobot technology evolves, these modes increase, making HRC even smoother and more efficient. In this context, guidelines for creating and deploying cobots in collaborative workplaces for HRI applications must be followed [15].

Furthermore, safety standards play an important role in supporting the safety of machinery and equipment on the markets of the European Union, protecting the health and safety of users and consumers. Compliance with the Directive helps to ensure that machinery is planned, built, and used properly, reducing risks and preventing accidents and injuries. These standards outline the design, implementation, and operation of cobots. Also known as harmonised standards, they represent the only method for designing a system, defining its state of the art, and making it interoperable with other systems. These criteria are not essential for designers, but they must be followed to ensure the quality and safety of cobot implementations in industrial processes [16-18].

Safety assessments have been crucial in the design of HRC tasks. A thorough risk assessment for HRC applications is pivotal to increase productivity and efficiency of the HRC tasks. This paper highlights the design of a risk assessment for the implementation of cobots in a manufacturing assembly task set up in a laboratory environment, where participants accomplished the tasks in two different scenarios: i) standard scenario – in which the participant performed the task without any intervention in the workplace; ii) collaborative scenario – in which th participant performed the task in collaboration with the robot. The robot deployed for the tests is the industrial MELFA ASSISTA cobot. The safety evaluation of the collaborative task is carried out through the matrix risk assessment defined for HRC applications. Further evaluation of efficiency of the assembly tasks performed by the participants in the two scenarios is carried out through observational measurements (checklist) for a complete analysis of the performance in both scenarios.

2 MATERIAL AND METHOD

The laboratory scenario is a realistic representation of an industrial assembly workplace, spanning from simple to complex interactions between people and cobots. Figure 1 depicts the workspace where participants conducted the tests.

Figure 1. Workplace setting

The working area has been customised with novel technology to accurately simulate the complex situations found in a natural work environment and to allow for better examination of participants' behaviour during manual assembly operations. This workstation features an industrial computer that monitors and manages the execution of various job duties, does process monitoring, and communicates with the operator via HMI devices. A touchscreen PC is linked to the system to define tasks and deliver stimuli [19].

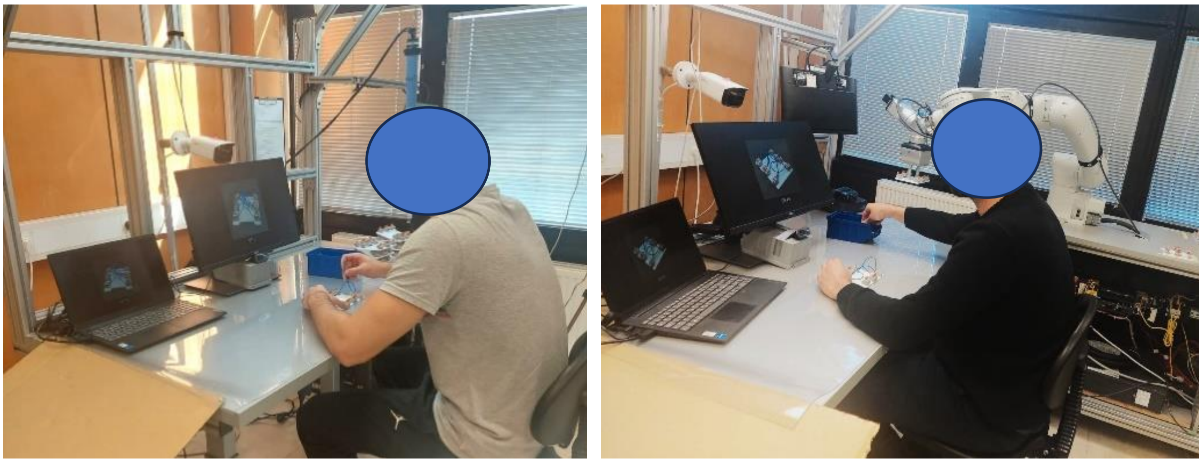
Aside from that, lighting is carefully planned. Lighting is a critical component in the ergonomic design of an assembly workstation. It is vital to provide a sufficient light source to avoid straining their eyes while performing work chores. Individual reflectors that produce superimposed solid shadows can cause eye strain, fatigue, and a lack of attention. Homogeneous LED lighting was installed on the new industrial lean workstation because it provides soft shadows that are gentler on the eyes. There is also an audio 5.0 system that recreates the noises of the industrial area [20].

The idea is for improving performance and productivity of the participants with the implementation of the robot in the workplace.

Based on workstation construction and integrated elements, two basic scenarios might be developed for purposes of comparative worker behaviour evaluations, as described in the Table 1 and shown in Figure 2.a and 2.b below:

Table 1. Description of the standard and collaborative scenarios

Name - Abbreviation	Description
Standard Scenario - SS	Manual assembly ativities are completed without any specific intervention or enhancement at the workplace. Work is done on the workstation "as is" with no intervention from other systems.
Collaborative Scenario - CS	Participants complete work activities collaborating with a cobot, which performs repetitive, uncomplicated tasks that do not involve thinking or decision-making.



(**a**) (**b**)

Figure 2. a) Standard Scenario – SS; **b)** Collaborative Scenario – CS.

Each participant will be subjected to a total of nine assessment tests. Each test took 90 minutes. The total number of components necessary to complete each scenario was 75. The distribution of the components was random. The situations occurred throughout the year, with a minimum length of four months. The goal was to eliminate recollection bias when comparing the cognitive burden across three scenarios [21].

This job, like wire-harness assembly activities, was chosen since there has been little study on the neuroergonomic analysis of these tasks when supportive technology, such as robots, is used. These harnesses are widely used in a variety of industries, including automotive, aviation, electronics, and industrial machinery. The assembly process is comprehensive, requiring precision and careful attention to detail. These tasks require a combination of manual dexterity, attention to detail, and the ability to comprehend complex wiring diagrams [22].

In the collaborative setting, Mitsubishi Electric's MELFA ASSISTA MITSUBISHI industrial cobot, as shown in Figure 3a, was deployed for testing. This cobot is designed to operate with people in a variety of manufacturing environments. It has safety features including collision detection and compliant mobility, which allow it to halt or change its direction if it encounters an obstruction, such as a human coworker. This makes it suited for collaborative workstations, eliminating the need for standard safety barriers. These cobots have simple programming interfaces, and they can occasionally be controlled and programmed with touch panels [23].

Another important feature of the design was choosing the right end-effector to hold the components and allow the robot to interact with its environment and the operator in the workplace. The design and effectiveness of an end-effector are heavily influenced by the robot's intended use. The robot end-effector used to carry the components was the VGC10 Electrical Vacuum Gripper, which is appropriate for HRI operations, as shown in Figure 3b.
Unlike standard hoover grippers, which run on compressed air, an electrical hoover gripper, such as the VGC10, is driven by electricity. Because it lacks pneumatic infrastructure, it is frequently more energy efficient and easier to integrate into multiple systems. These grippers are typically compact and lightweight, making them suitable for use with smaller industrial robots or cobots. Their size and weight allow them to be easily placed on a variety of robotic arms [24].

(**a**) (**b**)

Figure 3. a) Collaborative MELFA ASSISTA robot; **b)** VGC10 Vacuum gripper

In HRC tasks, the risk matrix for mechanical risk assessment is used to measure the level of safety in the collaboration scenario [25]. A complete mechanical risk assessment is essential for preventing accidents and injuries, maintaining regulatory compliance, and instilling a safety culture in workplaces where machinery is used. The first step is to identify all potential hazards related with the machinery. This includes moving elements that can cause injuries, points of operation, hot surfaces, electrical dangers, and any other aspect of the apparatus that could endanger the operators or people nearby.

Once hazards have been identified, the next step is to analyse the risk associated with each. This comprises the likelihood of the hazard causing an injury or accident, as well as the gravity of the outcome. The frequency of danger exposure, the number of people impacted, and current management strategies are all examined.
The Risk Class Index (CI) is estimated using the formula:

$$CI = Fr + Pr + Av \tag{1}$$

From the guidelines:

- Fr (Frequency): it evaluates the average interval between frequency of risk exposure and its duration and can assume an integer value between two and six. Indeed, as described in Table 2:

Table 2. Description of the levels of risk frequency

Level	Description
2	The time between exposures is more than one year.
3	The time between exposures is one year or less, but more than two weeks.
4	The time between exposures is two weeks or less, but more than one day.
5	The time between exposures is one day or less, but more than one hour. If the duration is less than 10 minutes, these values may be lowered by one level.
6	The time between exposures is one hour or less. This value should never be decreased.

- Pr (Probability): it is the probability of occurrence of a hazardous event and can assume an integer value between one and five. Here, as described in the Table 3:

Table 3. Description of the levels of risk probability

Level	Description
1	Negligible: There is no chance of human error occurring.
2	Rarely: Human error is highly unlikely.
3	Possible: Human error could occur.
4	Likely: Human error is probable.
5	Very high: Human behavior makes the likelihood of error very high.

- Av (Avoidance): it is the possibility of avoiding or limiting harm and can assume an integer value equal to one, three or five. Here, as described in the table 4 below:

Table 4. Description of the levels of avoidance in the risk assessment

Level	Description
1	Contact with moving parts behind an interlocked guard is likely to be avoided in most situations.
3	There is a possibility of avoiding an entanglement hazard when the machine speed is slow.
5	Avoiding an entanglement hazard is impossible if a part of the machine becomes live due to faulty electrical insulation.

Finally, for a comprehensive and consistent evaluation of the implementation of the cobot in the collaborative scenario, a well-designed checklist ensured that all critical aspects of productivity are considered. It helps avoid overlooking important elements that might be missed in a more informal evaluation. An open question is asked to answer at the end of the tests to evaluate the fluency of the task with the robot.

3 RESULTS

The matrix is separated into three areas, as indicated in the image below: The red region indicates that safeguards must be implemented immediately to decrease risk; the yellow area indicates that protective measures should be implemented to further reduce risk; and the green area indicates that the risk has been sufficiently reduced.

In this sense, given the collaborative scenario performed, the appropriate values to mark in the risk matrix are:
Se = 1: given that the robot's speed is set to collaborative mode (250 mm/s) and the component is lightweight with no sharp edges, the participant may only sustain scratches during the interaction with the machine.

Fr = 6: the interaction with the robot happens less or equal to 90 seconds.

Pr = 2: human error is improbable. The participant sits throughout the activity, keeping a safe distance from the cobot to avoid contact while it moves. The component may drop from the cobot's gripper. However, since the distance between the cobot and the participant is set to a safe value, the probability is extremely low. Furthermore, the participant may grab the item before the end-effector enters the manual assembly task. In this situation, the robot's inbuilt safety sensors would provide a warning signal noise indicating that the piece had been removed before the robot's movement ended. However, the robot's brain recognises this condition and indicates that the robot can go to the next task, returning to its original position to grasp the next piece. This condition never occurred throughout the testing. As a result, we assigned a value of 2 to indicate an improbable likelihood of human error.
Av = 1: there are no barriers between the human and the operator, but collision avoidance is ensured because the participant remains in the same position throughout the task, and the cobot motion at low speed and at a reasonable distance determined by safety guidelines, is not in contact with the participant's body.

Thus CI = 6 + 2 + 1 = 9. The risk is adequately reduced, as shown in Figure 4.

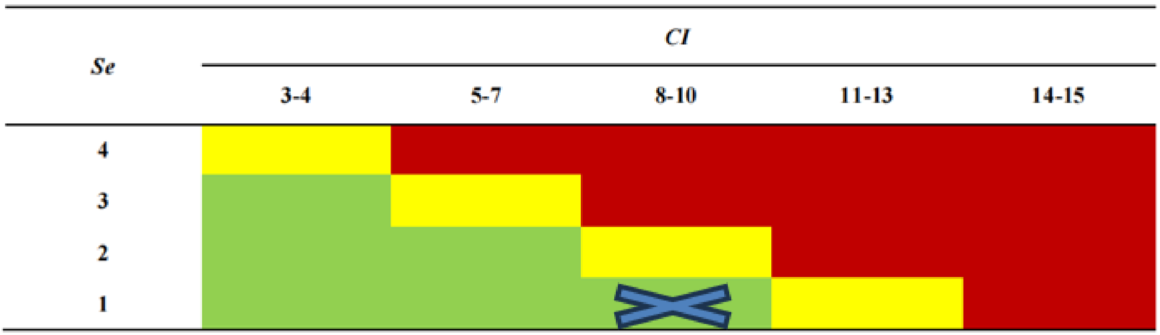


Figure 4. Risk assessment matrix

At the end of the experiments, participants had to answer open questions about their experience with and without the robot, its unpredictable motion and trajectory (whether predictable or not), how safe and comfortable the interaction with it was, whether the workplace setting was better in the standard or collaborative scenario, and how they perceived the workplace environment in terms of safety when they were performing the task in the two scenarios.
According to their responds, the assembly task with the robot resulted in a more secure and convenient method for removing the plate from the gripper. Furthermore, the participation was seen more informative and pleasant. In terms of motion, the participants were not terrified when the robot moved, and its reaction when they grabbed the pieces from the gripper was nonviolent. Furthermore, the absence of plates on the workstation where the participant installed the component was highly received in the collaborative context. Because they were less distracted, candidates had more room for assembling the component and were more confident in their ability to finish the task. Finally, in terms of workplace safety, the participant felt confident in carrying out the activity. In the collaborative scenario, participants believed that working with the cobot was safe and relied on the machine's motion and trajectory pathway throughout the tasks. Overall, the participants felt safe working in the workplace, connecting with other modules, and completing the assignment.
In accordance with the checklist-based observational research of participants' performance in the three situations, candidates performed the task more successfully in the CS and GCS than in the SS, as shown in Table 5. The T-test comparing performance across three circumstances revealed a P-value of 0.00018 ($< \alpha = 0.05$).

Table 5. Productivity index result in the standard and collaborative scenarios

Candidate Number	N. components accomplished in SS	N. components accomplished in CS
1	48	62
2	39	64
3	60	72
4	49	54
5	52	61
6	40	46
7	34	65
8	45	55
9	65	74

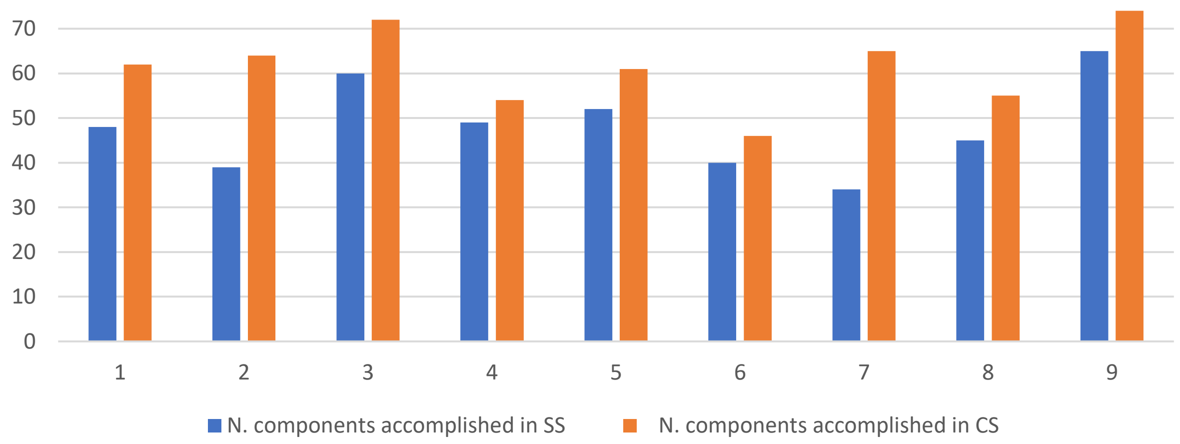


Figure 5. Productivity results in the standard and collaborative scenarios

The productivity index, shown in Figure 5, is increased of roughly 28% in the CS. These results are consistent with other studies.

4 CONCLUSION

The integration of cobots in factories and work systems has increased in recent years. The increased use of these technologies in fenceless industrial zones has motivated researchers to look into the operator's safety when interacting with the robot. The cobot station was setup in the workplace using a stiff workstation design that prioritised safety [26]. Manual assembly techniques, including wire harnessing, continue to be a barrier in industrial processes. This has prompted the development and investigation of HRC systems that let operators to collaborate with robots. Although the findings are significant, it is important to note that the research was conducted in a controlled setting, such as a laboratory.

Participants completed the activities in all three conditions while sitting in an enclosed workplace. However, motion artefacts and noise are usually dominating in industrial activities, and their presence may influence the risk assessment.

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