Overview of Ergonomics and Safety Aspects of Human-Cobot Interaction in the Manufacturing Industry

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Abstract. The technological advancements accompanied by Industry 4.0 have created more opportunities for collaborative interactions between humans and machines. In work environments where humans work alongside collaborative robots (i.e., cobots), there is a critical need to address ergonomics and occupational safety (ergo-safety) issues so that the work systems concerned can function optimally. As such, this paper investigates the ergo-safety determinants of human-cobot interactions in the manufacturing industry. The collaborative nature of the work system concerned will be discussed by considering humans as the leader of the ergo-safety implementation and cobots as the machine to allow deeper insights into the interaction between humans and cobots. The literature review first examines the involvement and impact of ergonomics with the safety implications that ensure safe collaboration. The main challenges in developing human cobots and implementing such systems in the industry are then discussed. It is found that there is an urgent need for optimizing human-robot collaboration when designing such systems. The outcomes of this overview would be of interest to the researchers and practitioners working with or developing Industry 4.0 systems. Moreover, the need to consider Human-Cobot System (HCS) integration and optimization in developing an advanced framework for addressing ergo-safety issues with specific improvements in optimization and cybersecurity is highlighted.

Keywords: Ergonomics, Safety, Human-cobots interaction, Collaborative robots.

1 Introduction

Ongoing advancements in industrial technologies pave the way for manufacturing companies to compete smarter in a dynamic business environment. For example, recent developments in the Industry 4.0 space have reshaped the notion of human-machine interaction to mean human-robot collaboration [1, 2]. Implementing collaborative robots (cobots) involves humans and robots collaboratively accomplishing tasks in a workspace instead of eliminating the human aspects in the work environment [3, 4]. In

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addition to the collaboration aspect, the performance of the work system would be affected by the attributes such as the pace, fidelity, and reproducibility of the cobots, as well as the cognitive abilities, such as information processing, communication, and problem-solving, of the human [5, 6].

A growing body of literature recognizes the emergence and importance of the human-cobot collaboration system and the context in which they operate. One aspect of the context is the physical boundary. It specifies whether the installation of a system introduces a different physical space, whether robots and humans share a direct physical workspace, or the collaboration is the core interaction in the system by means of data, visual, or auditory modes in haptic/tactile communication [7, 8]. The second aspect is the hierarchical task system. It includes the decision-making process, the level of task applied, and/or the cognitive load required. Humans and robots could have a particular hierarchy of planned and allocated tasks based on their capabilities and limitations. The human-robot automation hierarchy stretches from manual interaction, mostly from a traditional human-machine interaction, to balanced autonomous variability and further to the fully automated human-robot collaboration system [9, 10]. The third aspect is the support for effective and efficient functional collaboration between humans and cobots, which includes ergonomics, occupational safety and health, and system optimization [11-14]. This paper will focus on the third context, as this context has rapidly evolved in recent times. The purpose is to find the research gaps and identify future research directions on that aspect of the context related to human-robot collaborations.

The organization of this paper follows the following structure. Following this introduction, the methodological approach briefly outlined the topic's state-of-the-art. Then the literature review findings are summarized following the structure outlined in Figure 1, leading to the development of the framework presented in Figure 2. Gaps in the current knowledge and future research directions are discussed in the next section, followed by conclusions.

2 Methodology

In this paper, we used Systematic Literature Mapping (SLM) [15] to identify future research directions and establish the state-of-the-art on the topic covering the perspectives of ergonomics, safety, and system optimization of cobots. Various cobot systems are included, from the micro level, i.e., case study on a particular system implementation, to large-scale industrial implementation. The gaps are identified and mapped to highlight future research directions. The relevant articles were searched using the criteria incorporating the ergonomics and safety considerations on human cobot interactions, followed by an analysis for identifying the trends covering a period of 23 years since 2000.

The mapping from the literature review's findings is built upon the hierarchy displayed in Fig 1. The first structured layer is the system. This layer describes the human-cobots collaboration. The next layer is the sub-system layer which describes the focus of this research, such as the ergonomics considerations and the safety measures. The other two layers down the hierarchy cover elements and sub-elements, respectively.

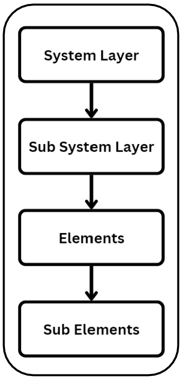

Fig. 1. SLM Hierarchy of the research

3 Ergonomics Considerations of Human and Cobot Interaction

3.1 Ergonomics Considerations

Ergonomics is an important consideration for collaborative robots (cobots) due to the nature scheme of the work, which collaborates with the man fellow in a working system. Ergonomic inputs are essentially depending on various factors, including the type of work the cobot will perform, the size and shape of the cobot, and the environment in which the cobot will operate [16].

It is predicted that automation technology will replace thousands of jobs in the future, and half of those jobs will be susceptible to an influx of new workers from all industry sectors [17, 18]. There are some discrepancies regarding new technology (autonomy) adoption that may affect the workforce. On the one hand, for example, women are considered to be more susceptible to an increased unemployment rate than men, and the effectiveness of work by a machine is better than a professional worker [17]. This situation would create gaps in the supply and demand for employment. On the other hand, ergonomics fit can provide a better system and help humans adapt to a new working system [19].

The ergonomics of humans-cobots interaction can be improved by maintaining an appropriate posture and body position configuration, developing autonomy, load optimization in tasks, and movement [20, 21]. There are some ergonomic aspects of the human-cobots interaction system, which are adjustable heights [22, 23], reduced force requirements [24, 25], collaborative workspace design [25-27], simplified user interfaces [28, 29], and end-of-arm tooling [30]. The specific work system needs to be developed to determine the best ergonomic design for a particular cobot application.

3.2 Ergonomics Method Implementation in Cobots Interaction

The ergonomic design of collaborative robotics necessitates that they be adjustable to accommodate varying human heights and workspaces. The objectives are to have flexibility in task execution, to maintain the comfort of the custodian, to facilitate cooperation for enhancing productivity, to optimize the workspace, to improve accessibility and reach, and to be able to adapt to product variations [20]. To accommodate the different heights and workspaces, the elements of the system should provide a degree of customizability that can extend or retract to adjust their height or multiple directions, such as telescoping arms, height-adjustable base, articulating arm, mobile base, and adjustable end-effectors [31-35]. The method that could be used to implement the adjustable heights and workspaces is divided into three stages.

The first step is the system identification involving the cobot model defined, the specific task requirement, workstations, and familiarization with the features. The second step is the implementation of the system, ensuring the required installation and safety mechanisms. Additionally, the function should be tested, verified, and implemented, guided by ergonomics considerations. The third stage is administration compliance, including the fulfillment of the standards, operator training, schedule of maintenance and inspections, and document track adjustment. Implementing adjustable height for cobots in their environment is critical, which follows a systematic approach to ensuring proper setup and operation. Following these steps, systems can effectively implement adjustable height for cobots, improving their respective environments' versatility, operator comfort, and overall productivity [20, 31-35].

Collaborative workspace design is important in creating an ergonomic, efficient, and productive environment for the human-cobots system. The benefits that arise from the design of a collaborative workspace are as follows: having an improved interaction that allows no hitch collaboration, complementing skills and capabilities; having enhanced safety measures to ensure human well-being; and creating space optimization, ergonomics comfort, workflow optimization, integration of safety and system, task allocation and workload balancing, and also flexibility and adaptability. By considering factors such as human-robot interaction, safety, space optimization, ergonomics, workflow, and flexibility, the design can maximize the benefits of collaboration while ensuring the well-being of both human operators and cobots [25-27]. The must-have features to design a workspace where humans can work collaboratively with cobots are safety sensors, rounded edges, soft surfaces, flexible work cells, adjustable workstations, intuitive interfaces, and cobots with compliant motion [26, 36-38].

A systematic method to design a collaborative workspace should follow three levels. The first phase is to define the design specification, define what tasks and requirements are needed, establish the safety protocol, analyze the workspace layout, and determine ergonomic considerations. The second step is to implement the design, integrate safety sensors and systems, optimize task allocations, test and validate the design, and implement the design. The third stage is the administration process involving operator training and continuous evaluation and improvement. The overall implementation of the collaborative workplace design could help effectively facilitate seamless collaboration between humans and cobots [26, 36-38].

4 Effective Safety Measures for Human Cobots Systems in Manufacturing Industries

4.1 Safety of the Human Cobots System

In 2020, New South Wales reported 53 workplace-related fatalities out of a total of 194 fatalities across all States in Australia, with the most significant proportion of workplace accidents occurring from moving objects, machinery, and immovable traps, accounting for 35% of the total. Technological influence represents a significant proportion of the contribution to those accidents; however, there is no clear category and contribution for the technology used (e.g., collaborative robots) [39]. Since technological advancements are ongoing, adaptation to new technology must be done systematically. Additionally, significant efforts must be put into comprehending how safety and health are included in planning the physical environment and the workplace. Industry 4.0 developments force the design of occupational health and safety safeguards to ensure the well-being of humans and cobots.

Moreover, innovative solutions to address the challenges posed by Industry 4.0 should be developed by involving all necessary viewpoints from workers, managers, experts, and government regulators. A framework should be developed by incorporating different perspectives of experts. Therefore, a comprehensive OHS framework must be developed to overcome these challenges, meet the requirements for flexibility of the future autonomous and cobot environments, and secure future generations to work in a safe and prosperous atmosphere [17].

Safety risk assessment is a process of identifying the overall scenarios of performing the work and the overall hazards involved, followed by assessing, addressing, and evaluating the preventive and corrective safety measures [40, 41]. Risk assessment can play an important role in creating a safe and productive cobot environment by identifying potential hazards, developing effective safety measures, ensuring compliance with safety standards, and improving operational efficiency [27]. Overall, risk assessment is a critical process to ensure the safe operation of cobots in workspaces involving human operators. Organizations must ensure that their cobot systems operate safely and effectively by identifying and mitigating potential hazards through a systematic and comprehensive risk assessment process [25, 27].

The use of cobots in the manufacturing industry offers many benefits, including increased efficiency and productivity, improved quality, and reduced costs. However, it is critical to confirm that human workers working alongside cobots are safe. Safety measures must be adequate and effective where a complete evaluation is carried out for risk identification by considering the overall process interactions, affordability, as well as preventive and corrective measures [27, 28, 42, 43].

4.2 Safety Measures Implementation Method

Manufacturers implement safety measures for their work systems to protect and minimize the risk of injury to human operators and generate a safer work environment when using cobots in their operations. Organizations can create a secure and productive environment for cobots' successful integration and operation by prioritizing safety. Safety measures should be considered in applying occupational safety and health for human-cobot systems, which are risk assessment, safety sensors, safety software, safety barriers, training, and maintenance [25, 28, 43-50].

Risk assessment is critical. The in-place risk assessment includes identifying potential hazards, developing safety measures, ensuring compliance with safety standards, and improving operational efficiency. This could enhance the implementation of the human-cobot system and secure the operation [25, 44-46]. There are several types of risk assessments that can be conducted in identifying and mitigating the potential hazards associated with cobot operations, such as preliminary hazard analysis (PHA), ISO 12100, failure mode and effects analysis (FMEA), ISO/TS 15066, and the hazard and operability study (HAZOP) [40, 45, 51-55] protocols. The systematic method to perform risk assessment in a human-cobot environment could be divided into three stages. The first step is defining the context through hazard identification, determining the harm likelihood and severity, evaluating the risk, and identifying control measures. The second step is implementation, and the third is monitoring and reviewing. Overall, manufacturers need to implement effective risk assessment measures to ensure the safe operation of cobots in their specified environments [44, 45].

Safety barriers such as physical or cage and infrared could prevent injuries. However, the development of cobots is considering the collaborative interaction without barriers yet convinced to still be in the safe zone [56, 57]. There are some benefits to the implementation of safety barriers, such as physical separation to create a safe, designated space in between, restricted access in the immediate vicinity of the cobot environment, hazard containment, visual demarcation, emergency response facilitation, and compliance with regulation [46, 48, 58-62]. In addition, there are some safety barriers that are commonly used to support the safety operation of human-cobot interaction, for example, light curtains, safety mats, fences, shields, and vests [38, 63, 64]. It is noted that specific steps may vary depending on the cobot system, application, and local safety regulations. Moreover, one of the most significant steps to implementing safety barriers is to integrate within the safety control system to ensure coordinated operation; this may involve connecting sensors, switches, or interlocks to the cobots safety interface, which can stop or alter the cobots' behavior when the safety barrier is breached [48, 65].

5 Analysis of Human Interaction System with Cobots for Optimization

5.1 Facilitation of Human-Cobots Collaboration Optimization

Industry 4.0 is driving more opportunities for interactions between humans and machines (cobots), which has already been acknowledged, especially in defining safety aspects related to the effects of injuries and illnesses by collaboration [14, 66-71]. The working system for the humans-cobots interaction is comprised of humans, cobots (as the machine), and the environment to serve the function, considering humans taking the role of initiation and controlling of the cobots involving feedback and reciprocal action in consequence; all of these circumstances are prominent in the phase of human information processing [67, 72, 73]. Moreover, humans are susceptible to inducing errors irrespective of the nature of safety events [69, 70, 74, 75]. Some arguments consider humans as the leader in safety implementation, and cobots (as the machine) and the atmosphere involvement lead to an understanding of using workers' perspectives in evaluating the interaction between humans and machines [66, 76].

The circumstances of human-robot collaboration can cause stress and reduced productivity; hence, smooth collaboration needs to be optimized so that the stress, especially anxiety, emotion, and mental load, can be managed comfortably and overcome the challenges at hand [3, 5, 6, 77, 78]. In addition, human-cobot interaction can be challenging to learn and adapt; hence operator training should be required and supplemented to address the safety issues involved [79, 80].

The need to combine ergonomics and safety to understand and improve human-cobot system interactions can be made effective by applying optimization. The methods used in human-cobot interaction optimization that started to be used by researchers are process improvement, feedback systems, training and skill development, sensor and technology development, and continuous monitoring and evaluation [22, 25, 26, 81-86]. The phase of the evolvement of the human-cobots interaction process improvement exhibits the need for adaptation to new technology and/or other elements to support safe collaboration [81, 82]. In addition, the development of the human-cobot system should also integrate a feedback system to learn and improve the necessary modifications [26, 83]. Moreover, because of the evolvement of adaptation, the collaboration system is also enhanced by training and skill development for better efficacy and circumstances [84, 85]. On the other hand, the latest sensors and technology must include process improvements to support ergonomic and safe collaboration [22, 25]. Ultimately, this development process will not succeed without ongoing and continuous monitoring and evaluation to support additional changes and adaptations [82, 86]. Overall, a synthesis of what was found in the overview is presented in Fig 2.

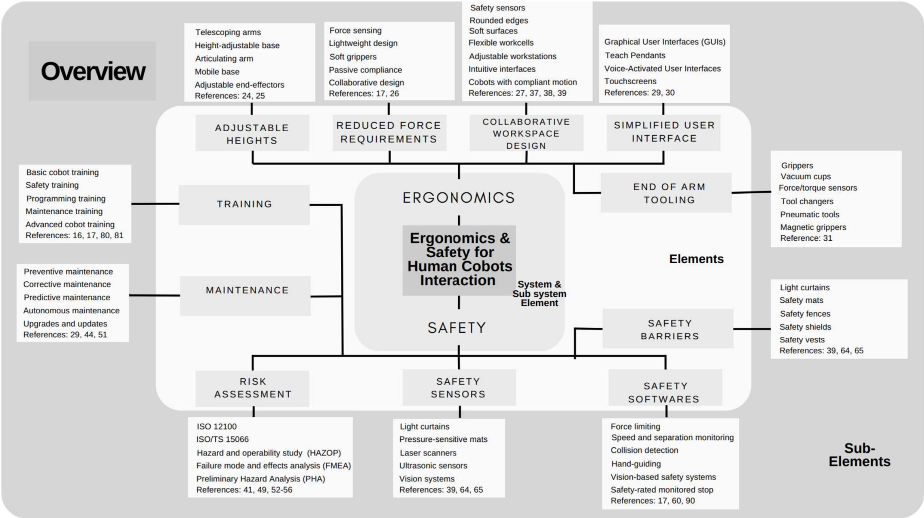

Fig. 2. Mapping of the research for the Human-Cobots Interaction System

6 Gaps and Future Opportunities for Researching Human-Cobots Interaction System

Human-robot collaboration optimization involves designing and implementing collaborative robot (cobot) systems that maximize productivity, safety, and comfort for both humans and robots. Some gaps should be addressed to enhance the integration of ergonomics and safety considerations for successfully implementing an HCS. The first gap is the partial ergonomics considerations in the design of the overall elements of HCS [26]. There should be a comprehensive and systematic approach to cover overall human aspects, especially in the ergonomics elements, not only one or few aspects involved, so that there are no missing parts of the ergonomics aspect that are addressed. For example, adjustable heights and collaborative workspace design elements should include the anthropometrics consideration, especially for the area or characteristics for the system to apply (e.g., Indonesia, Australia) [43, 47]. The second consideration is the evolving algorithm applied to reducing the workload and improving the integration of the HCS [87, 88]. New algorithms need to be improved to consider ergonomics and safety aspects for collaboration. The next improvement could be made using simulation-based optimization [25, 27]. The simulation could help map the current condition and replicate the improvements without endangering the human and cobots involved. Moreover, the simulation could combine virtual and case-based rather than only physical case-based simulation (in the laboratory). Furthermore, the consideration of safety needs to be integrated and comprehensive [25, 45, 55, 89]. Safety aspects are critical to have in the HCS as the mechanisms to ensure unharmed humans and effective collaboration.

There are some limitations that arise from the discussion on safety issues. One of these issues is cybersecurity. Cybersecurity is essential for ensuring the safety, integrity, and reliability of cobots and their environment [59, 90]. By implementing robust cybersecurity measures, organizations can protect the cobots' environment from potential cyber threats, ensuring the availability, integrity, and confidentiality of the data and the systems. This protects the organization's assets, operations, and reputation while enabling humans and cobots to collaborate safely and securely. Ensuring cybersecurity is an essential aspect of implementing any technology, including cobots. Several types of cybersecurity measures are available to enhance the security of cobots, for example, risk assessment, access control, network security, software updates, data protection/encryption, application security, security monitoring and incident response, and physical security [25, 59, 90]. The manufacturing context should be integrated to cover various implementations of the human cobots interaction, whether the traditional manufacturing company, modern, smart factory or specific area, assembly, welding, or sawing [1, 3]. There is a need for studying the issue of the compliance of ergonomics, safety, and optimization, and also a need for advanced research on the cybersecurity of human-cobot systems.

7 Conclusion

The evolution of the interaction, from the ergonomics, safety, and system optimization perspective, needs to be addressed in developing a better HCS. There are various methods discovered, from microsystems (study cases on particular system implementation) to large-scale industrial implementation, to address the issues in literature. The gaps that emerged are the ergonomics consideration in the design, new algorithms, simulation-based optimization, and safety concerns. Moreover, the gaps will need to be acknowledged and mapped so that future research can be defined well to address the issue.

There is a need for the integration and optimization of the HCS so that comprehensive analysis can be performed and there will be an effective, efficient, healthy, and safe collaboration between humans and cobots. This integration could be developed into an advanced framework that could be developed as a standard specifically for human-cobot interaction systems. There is also room for improvement in optimization and cybersecurity that should be considered well during the research on human-cobot interaction.

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