Safety Science 169 (2024) 106313

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Occupational health and safety issues in human-robot collaboration: State of the art and open challenges

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ARTICLE INFO

Keywords:
Industry 4.0
Human-Robot Collaboration (HRC)
Hazard
Risk
Safety

ABSTRACT

Human-Robot Collaboration (HRC) refers to the interaction of workers and robots in a shared workspace. Owing to the integration of the industrial automation strengths with the inimitable cognitive capabilities of humans, HRC is paramount to move towards advanced and sustainable production systems. Although the overall safety of collaborative robotics has increased over time, further research efforts are needed to allow humans to operate alongside robots, with awareness and trust. Numerous safety concerns are open, and either new or enhanced technical, procedural and organizational measures have to be investigated to design and implement inherently safe and ergonomic automation solutions, aligning the systems performance and the human safety. Therefore, a bibliometric analysis and a literature review are carried out in the present paper to provide a comprehensive overview of Occupational Health and Safety (OHS) issues in HRC. As a result, the most researched topics and application areas, and the possible future lines of research are identified. Reviewed articles stress the central role played by humans during collaboration, underlining the need to integrate the human factor in the hazard analysis and risk assessment. Human-centered design and cognitive engineering principles also require further investigations to increase the worker acceptance and trust during collaboration. Deepened studies are compulsory in the healthcare sector, to investigate the social and ethical implications of HRC. Whatever the application context is, the implementation of more and more advanced technologies is fundamental to overcome the current HRC safety concerns, designing low-risk HRC systems while ensuring the system productivity.

1. Introduction

Human-Robot Collaboration (HRC) refers to the interaction between workers and robots to complete tasks in a shared workspace (Boston Consulting Group, 2015). In the current increasingly competitive global and dynamic market, affected by the technological advancement of the fourth industrial revolution (Jamwal et al., 2021), collaborative robotics is of considerable interest for manufacturing companies that need to move from mass production to mass customization, in order to enhance their market position. This change of paradigm implies the use of advanced and sustainable production systems, characterized by a scalable degree of industrial automation to meet the increasingly pressing demands for flexibility, efficiency, product variants and time-to-market. In this context, collaborative robotics enables the integration of the industrial automation strengths with the irreplaceable cognitive human capabilities, improving the production systems performance and the workers' well-being as a result (Bauer et al., 2008; Siciliano and Khatib, 2016). Repetitive and challenging tasks, either physically or cognitively, may be hence accomplished by COllaborative RoBOTs (i.e. cobots), while relieving human operators. Besides the industrial sector, cobots have been also employed in other areas, such as surgery, education, and agriculture (Jacob et al., 2012; Bergerman et al., 2015; Amarillo et al., 2021; Moysiadis et al., 2022), and the global market is projected to exponentially grow up in the next years (IFR, 2019; Galin and Mamchenko, 2021) (Fig. 1).

Nevertheless, robotics and worker safety are unavoidably intertwined, and the inclusion of cobots in work environments can raise new safety concerns. On the one hand, workers are kept physically separated from robots by means of safeguards (physical or sensor-based) in traditional robot applications, where equipment are stopped as soon as the worker crosses the so called safeguarded space (ANSI/RIA R15.06-2012, 2012). On the other hand, properly designed collaborative

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https://doi.org/10.1016/j.ssci.2023.106313
Received 12 May 2023; Received in revised form 30 August 2023; Accepted 11 September 2023

systems are implemented in HRC to ensure safe conditions, without any human-robot separation (Franklin et al., 2020; RIA TR R15.606, 2016). As a result, HRC exposes workers to new hazards and risks (e.g. mental stress of operators owing to the robot proximity), while likely reducing other ones (e.g. reducing and/or deleting potential physical injuries due to repetitive motions) (Soto-Leon et al., 2020; Agnusdei et al., 2022; La Fata et al., 2023).

Although the overall safety of collaborative modes has increased over time, designing and implementing inherently safe and ergonomic automation solutions still remains paramount to allow humans to operate alongside robots without safety barriers. In addition, both the complexity of used automation technologies and the human unpredictability drive towards a new way to analyze hazards and assess risks in collaborative environments. Obviously, safety constraints need to go at the same pace as performance requirements of collaborative systems, to ensure the smoothest and most efficient production processes (Gualtieri et al., 2021). As a result, a number of surveys and systematic literature reviews of HRC-safety related issues have been conducted so far. In this regard, Bogue (2017) conducts a survey of techniques and Standards concerning the safety of robots which operate in close proximity to humans, especially assistive, personal care and service robots, and mobile warehouse and delivery robots. Robla-Gomez et al. (2017) present a survey on safety systems and regulations proposed and implemented in industrial environments. Vasconez et al. (2019) and Benos et al. (2020) respectively explore Human–Robot Interface (HRI) strategies and ergonomic issues with relation to the agricultural sector. Gualtieri et al. (2021) conduct a systematic literature review – limited to the “engineering” and “computer science” subject areas – to identify the main researched safety and ergonomic topics in industrial HRIs. Bonci et al. (2021) provide a survey of sensory equipment used for human detection and action recognition during collaboration in an industrial environment. Grushko et al. (2021) focus on graphical, acoustic and haptic feedback implementations to improve the human awareness in collaborative tasks. Mukherjee et al. (2022) present a survey of machine learning strategies implemented in HRC environments. Kim (2022) carries out a systematic literature review of human resource development considerations (e.g. employee attitudes toward robots, readiness for robot technology, communication with robots, human–robot team building, ethical issue, etc..) to support organizations in implementing robotic systems. Hopko et al. (2022) propose a review of metrics and methods (e.g. questionnaires, bioinstrumentation, objective behavioral analyses, and mathematical representation) commonly used in collaborative contexts to measure the human trust, cognitive workload, and anxiety. Hjorth and Chrysostomou (2022) provide a review of autonomous robotic disassembly systems used for industrial disassembly operations while incorporating HRC.

However, the majority of available surveys and literature reviews focus on HRC safety through motion planning and control and compliance with Standards (Zacharaki et al., 2020), and/or deal with specific sectors. Differently, the main attempt of the present manuscript is to provide a comprehensive overview of Occupational Health and Safety (OHS) issues in collaborative environments, mainly focusing on the impact of the robot collaboration on the worker safety. Therefore, the analysis is performed under a human-centered perspective, seeking to answer the following Research Questions (*RQs*):

RQ$_1$: What are the main HRC-related topics and application areas addressed by practitioners and academics in the field?

RQ$_2$: What are the latest updates and open challenges on OHS in collaborative environments?

Accordingly, the most researched topics and application areas of HRC are firstly investigated by a bibliometric analysis. Afterwards, the literature review of a selected number of articles is conducted to deepen the effects of HRC on OHS, exploring emerging risks and improved ones. Control measures currently implemented – either in lab or industrial scales – to risks prevention and/or mitigation are also highlighted. Finally, future lines of research to be addressed to transfer collaborative robotics from a lab scale to a shop floor are identified.

The paper is organized as follows. Section 2 describes the methodological approach for the bibliometric analysis and the subsequent literature review. Outcomes of the bibliometric analysis are also synthetized in Section 2, underlining the most prolific countries and institutions in the field as well as the most researched HRC application

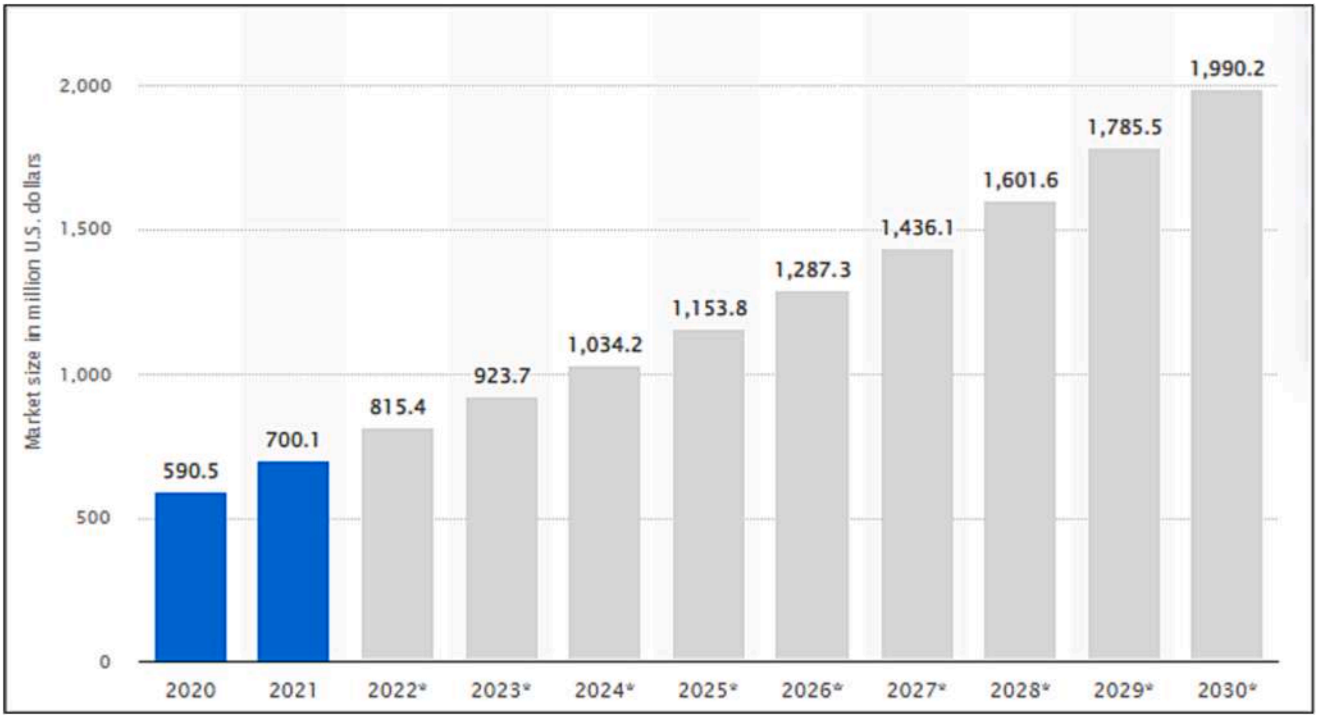

Fig. 1. Cobot market worldwide in 2020 and 2021 and forecast from 2022 to 2030. .
Source:www.statista.com

areas and topics. In Section 3, the literature review on papers selected as to be relevant to the intended objective is presented. Research findings and future challenges to extensively transfer collaborative robotics from the lab scale to the shop floor are discussed in Section 4. Finally, Conclusions are given in Section 5.

2. Research methodology and bibliometric analysis outcomes

A structured methodological approach comprising numerous consequential steps was employed to derive the main relevant contributions to answer the aforementioned *RQs*. Started in November 2022, the study made use of the Scopus database owing to its relevance, and the time span 1980–2022 was initially set to investigate the trend of documents over time. Step by step, based on set inclusion–exclusion criteria, documents falling outside the scope of the study were discarded, and the remaining ones were listed and passed on the final full-text analysis. Using the same inclusion–exclusion criteria, a further search was also performed on Web Of Science (WOS), within the time span 1993–2022. From the obtained list, documents already obtained by Scopus were removed, while the remaining ones were passed on the full-text analysis. As a result, the final list of documents on which performing the literature review was obtained. The inclusion-exclusion criteria which the research methodology was based on are synthetized in Fig. 2.

The first objective was to answer RQ_1, i.e. identifying the HRC-related topics and application areas that practitioners and academics in the field have addressed the most to date. To this purpose, the Scopus database was used, and keywords were properly linked by the logical operators of “AND” and “OR”. Therefore, searching for (collaborative AND robot) OR (collaborative AND robotics) OR “cobot” OR “human robot collaboration” OR “human-robot collaboration” within the field “Article title, Abstract, Keywords” of the Scopus database, a total number of 11,162 documents were returned (step 1). From Fig. 3, it is noteworthy how the number of documents is almost negligible from 1980s to 2000s, when robotics was at early stages. On the other hand, the number of documents has exponentially grown since 2011, which actually marks the beginning of the Industry 4.0 paradigm (Gualtieri et al., 2021).

Afterwards, only “Article” published in “Journal” and written in “English” were selected, reducing the initial set of 11,162 documents to 3,213 (step 2). Documents by country and affiliation are synthetized in Figs. 4 and 5 respectively.

To further refine the results, focusing on the most relevant papers in the field, only the ones published in Journals of the first quartile - for subject area of interest and year of publication - were selected. To this aim, the Scimago (https://www.scimagojr.com/) database was used along with an Excel spreadsheet, obtaining a set of 1,847 documents as a result (step 3). An initial bibliometric analysis was hence performed on this set of articles by the software VOSviewer (https://www.vosviewer.com/). Documents by countries, connected by co-authorship links, were firstly analyzed (Fig. 6), followed by the number of publications by Journal, connected by co-citations links (Fig. 7). The United States is confirmed in the first position with 505 documents, followed by China and Italy with 360 and 243 articles respectively. The Journal having the highest number of documents (i.e. 181) on HRC is IEEE Robotics and Automation Letters, followed by Robotics and Computer-Integrated Manufacturing (i.e. 85) and IEEE Access (i.e. 75).

By VOSviewer, the topics of interest covered by the literature in the field were also investigated by the keywords co-occurrence criterion in the “Article title, Abstract” field, properly removing repetitions or similar words referring to the same topic (e.g. HRC and human robot collaboration). A minimum number of six co-occurrences was forced. Meaningless words such as research, study, and case were also removed, so that 273 significant keywords were finally obtained (Fig. 8). Among others, it is noteworthy how the most frequent keywords are robotic, industry, workspace, and activity along with human safety-related keywords such as collision, movement trajectory, detection, and force. In addition, assembly appears as the most analyzed cobot application process. Furthermore, the analysis of co-occurrence highlights the paramount role of the human factor and safety in collaborative robotic systems, owing to the presence of keywords such as trust, posture, and human body. From Fig. 8, the widest investigated issues to scale up HRC also emerge, e.g. control algorithms and frameworks, Digital Twin (DT), Augmented Reality (AR), Artificial Intelligence (AI) and cloud technologies.

Subsequently, the set of articles obtained at step 3 was inserted in Scopus, and the query was updated to identify the main cobot application areas and tasks. To this purpose, words such as “manufacturing”, “industrial”, “production”, “healthcare”, “agriculture”, “construction”, “logistics” and “social” were added in the “Article title, Abstract, Keywords” field, while the logical operator “AND NOT” was properly used to avoid the multiple counting of articles. As highlighted in Fig. 9, HRC in the industrial, manufacturing and production area is the most researched one, followed by the social area which encompasses all those robots used to assist humans at the household level. Another area of application is the healthcare, followed by agriculture, logistics and construction. As concerns collaborative tasks, assembly takes the first position, followed by the quality check and inspection and the material handling (Fig. 10).

From the dataset of the step 3, documents containing words such as “design”, “programming”, “mechanics”, “movements”, “sensor” and “control system” within the “Article title, Abstract, Keywords” field were searched – avoiding the multiple counting of articles as previously stated by the “AND NOT” operator – to find out the most faced technical issues. Fig. 11 shows the obtained results, with the largest number of articles focusing on cobot design and movements, followed by studies on sensing systems and programming.

Afterwards, the analysis was focused on safety-related issues during human-robot collaborative operations, aiming to discover the latest updates and open challenges on OHS in collaborative environments (RQ_2). Among the 1,847 articles obtained at step 3, “safety”, “stress” and “risk” were searched within the field “Article title, Abstract, Keywords” of the Scopus database (step 4). The search was further refined by using the subordinate keywords “human”, “worker”, “working place”, “workplace” and “work environment”, so obtaining 347 articles (step 5). Finally, the query was updated searching for the keywords “injury”, “accident”, “hazard” and “health”, which returned a set of 113 articles (step 6). The distribution by country as well as the most researched OHS-related issues were analyzed by VOSviewer, whose results are showed in Figs. 12 and 13. The graph of Fig. 12 confirms the United States as the most prolific country, followed by China and Italy. On the other hand, Fig. 13 returns a first insight about the main safety challenges posed by HRC, with collisions detection, ergonomic and human factors as the most researched topics. Fig. 13 also highlights that Cyber-Physical Systems (CPSs), AR, DT – Industry 4.0 in general - and safety Standards are the widest studied issues to transfer collaborative robotics from a lab scale to a shop floor, while ensuring safe human-robot interactions.

3. Literature review

The full-text analysis was performed on the set of selected articles, with the aim of excluding the ones laying outside the scope of the literature review, i.e. identifying the latest updates and open challenges on OHS in collaborative environments (RQ_2). Therefore, documents purely dealing with technical issues (e.g. programming, mechanical features design, etc..) or deemed not to be relevant to the intended objective (i.e. RQ_2) were excluded. Summing up, 58 articles were finally selected and reviewed. As regards the OHS-related issues in collaborative environments, the selected list of articles confirms the results of the bibliometric analysis with relation to the application field, either sector or task (Fig. 14). The majority of selected articles deal with collisions (i.e. thirty-five articles), followed by cognitive workload and mental stress

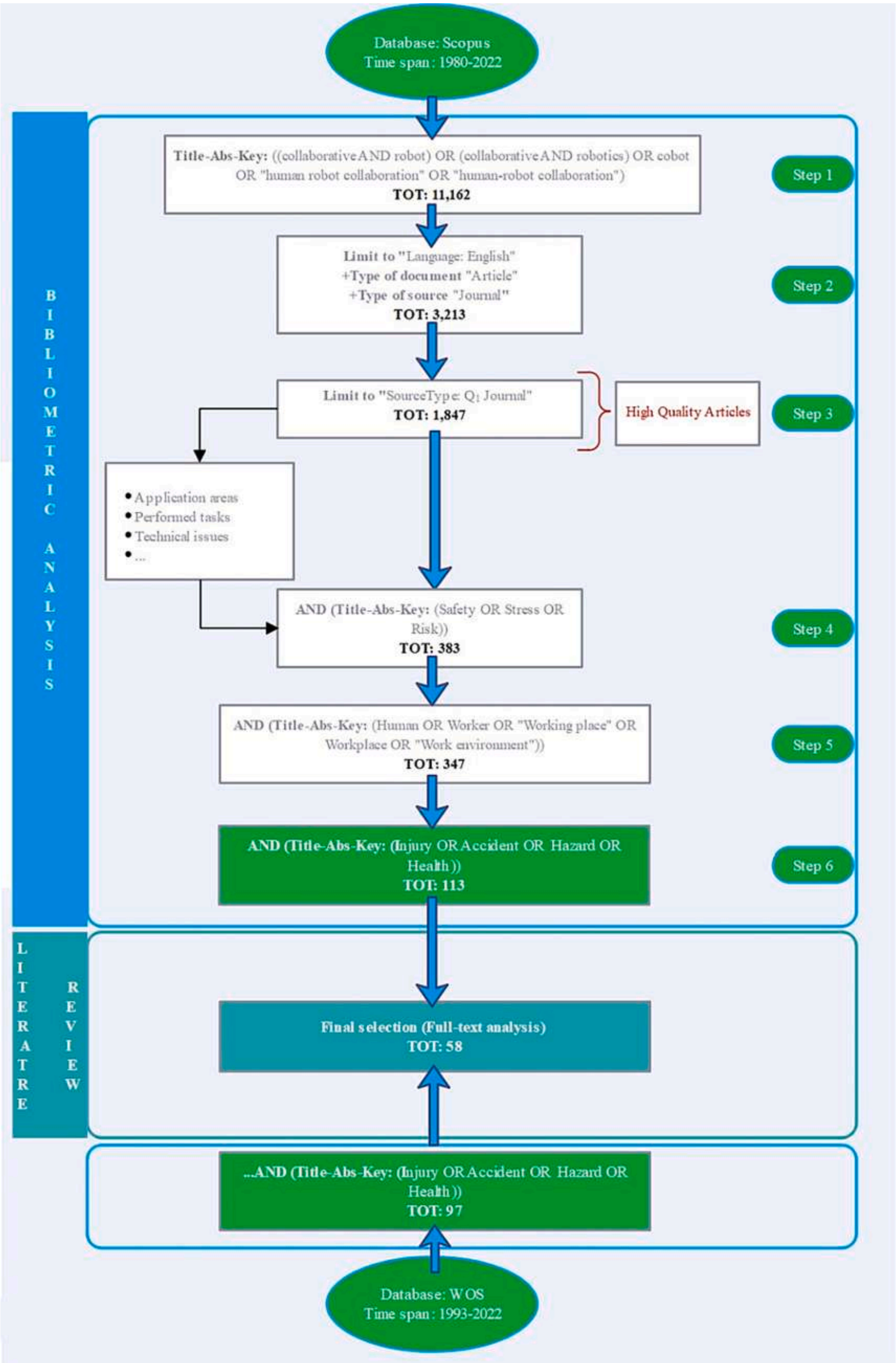

Fig. 2. Flow-chart diagram of the research methodology.

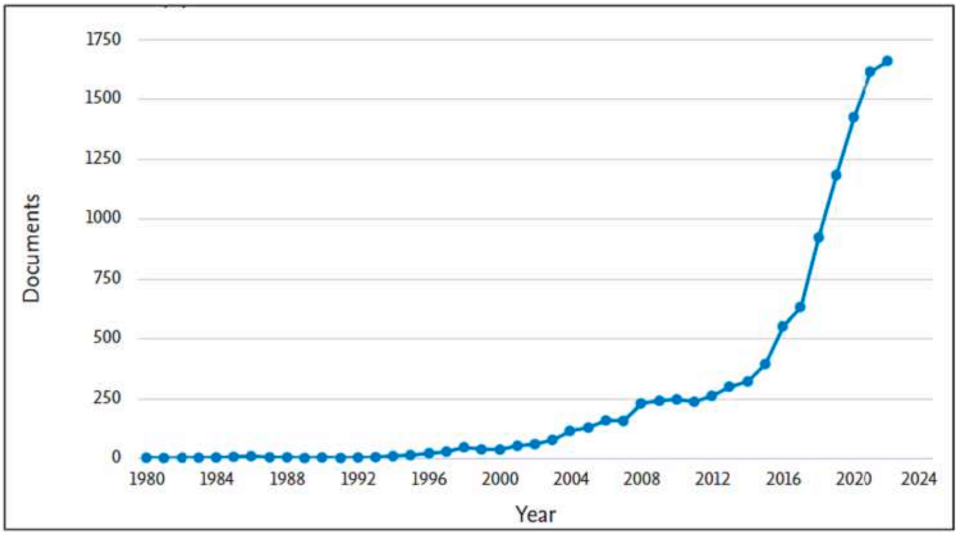

Fig. 3. Documents by year.

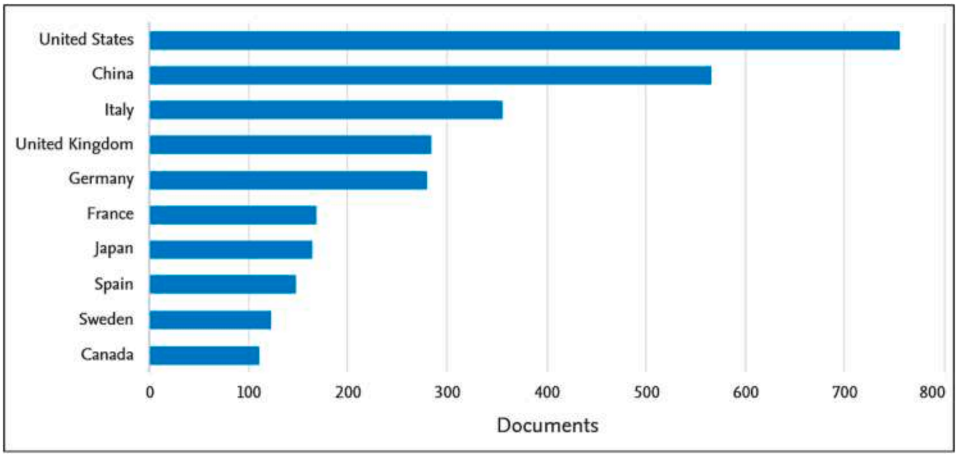

Fig. 4. Documents by country.

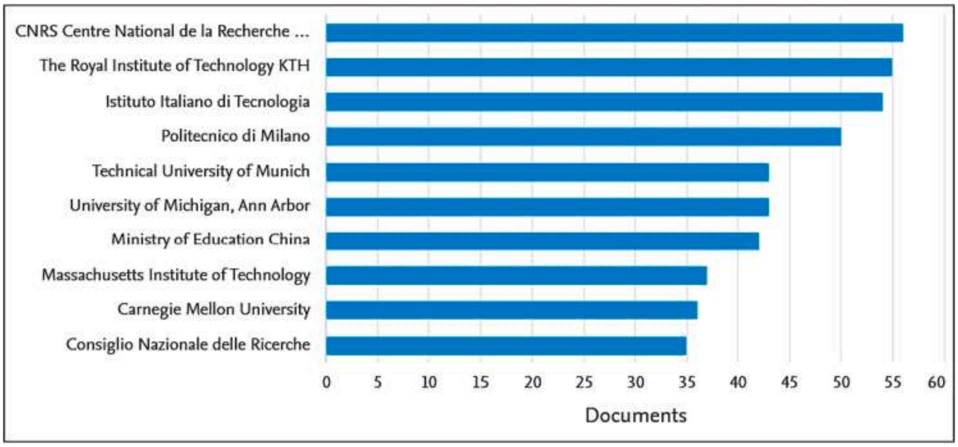

Fig. 5. Documents by affiliation.

(i.e. seven articles), ergonomics (i.e. eight articles), and cyberattacks (i.e. two articles). The remaining six papers focus on hazard analysis and risk assessment in HRC (Fig. 15). The literature review of the selected articles is provided in the following sub-sections.

3.1. Hazard analysis and risk assessment

According to the ISO 15066 Standard (International Organisation of Standardisation, 2016), carrying out a comprehensive hazard analysis

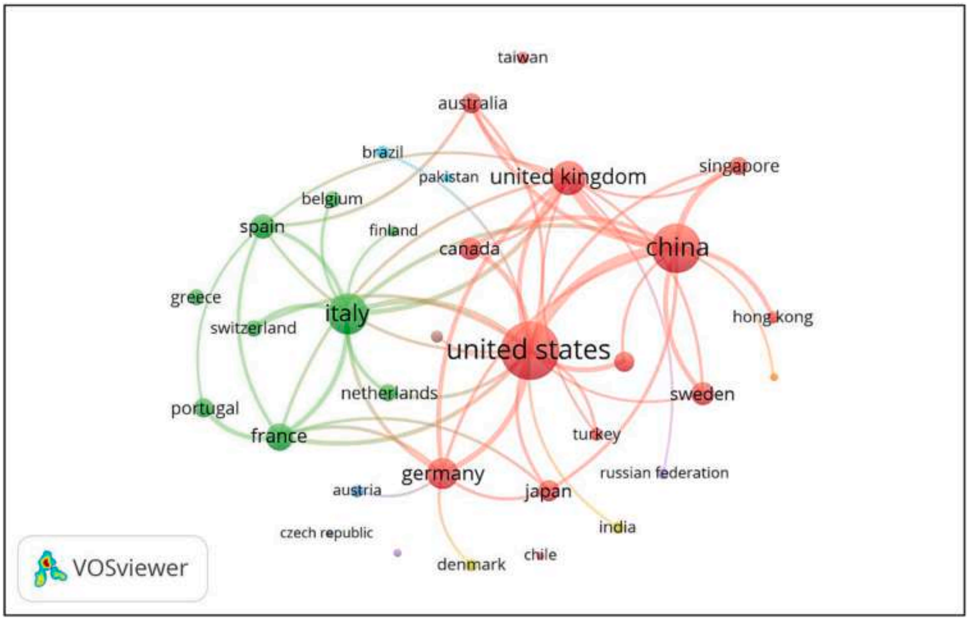

Fig. 6. Network of documents published in Q_1 Journals by country, with co-authorship links.

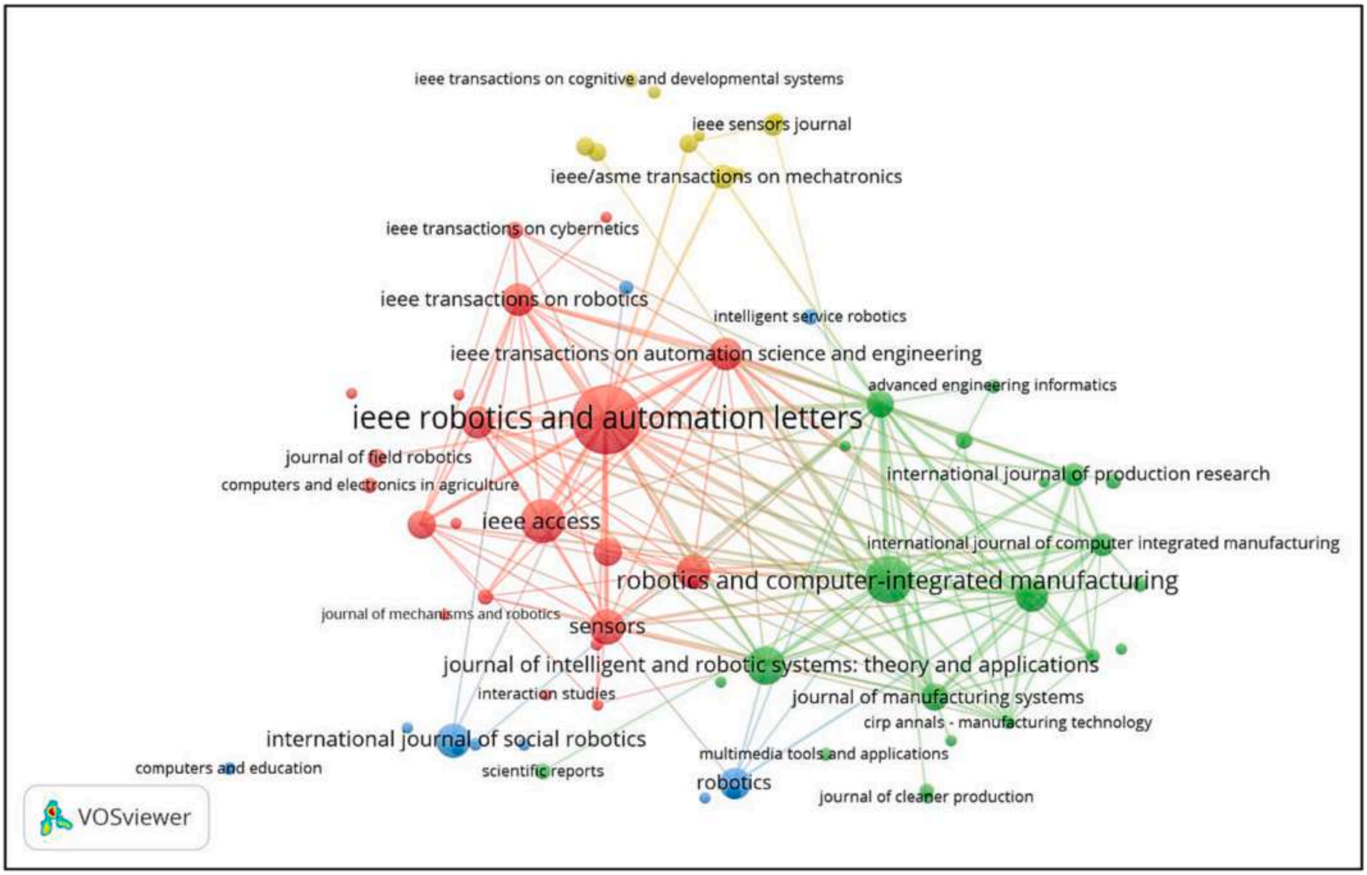

Fig. 7. Network of documents published in Q_1 Journals by source, with co-citation links.

and risk assessment remains paramount in collaborative robot systems to determine whether and which safeguards are needed to address the identified risks (Franklin et al., 2020). Despite that, Chemweno et al. (2020) claim the need of more specific guidelines on the way how the hazard analysis and risk assessment have to be performed in collaborative environments, paying specific attention to the human factor. In addition, a structured framework to align the safeguards design and the outcomes of the hazard analysis and risk assessment is still lacking. Accordingly, Huck et al. (2021) argue that risk assessment and mitigation procedures currently proposed by the normative Standards are mainly based on the expert knowledge. However, such a kind of expert-based approach is difficult to extend to HRC systems, owing to

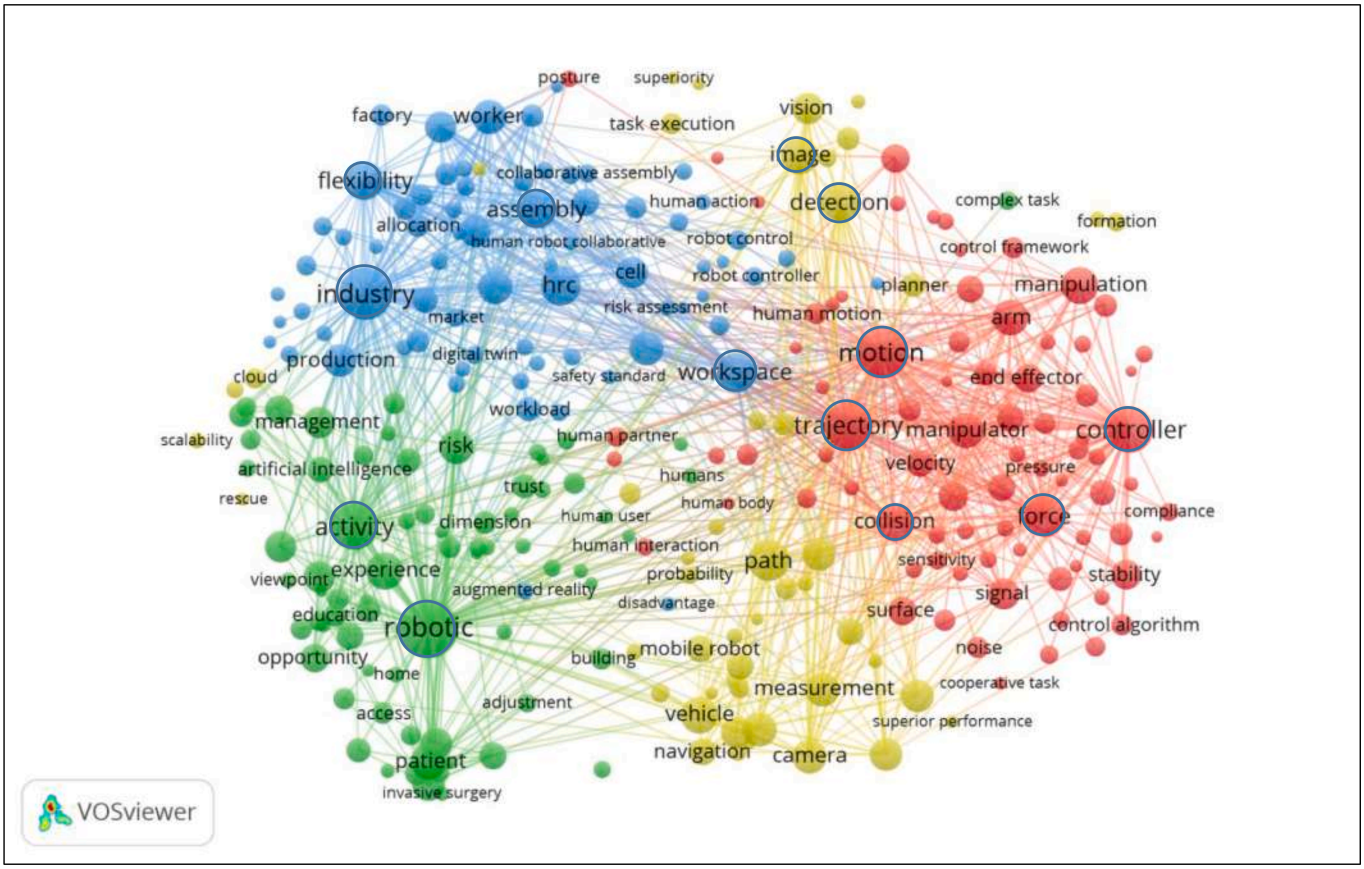

Fig. 8. Network of documents by keywords co-occurrence in article title and abstract.

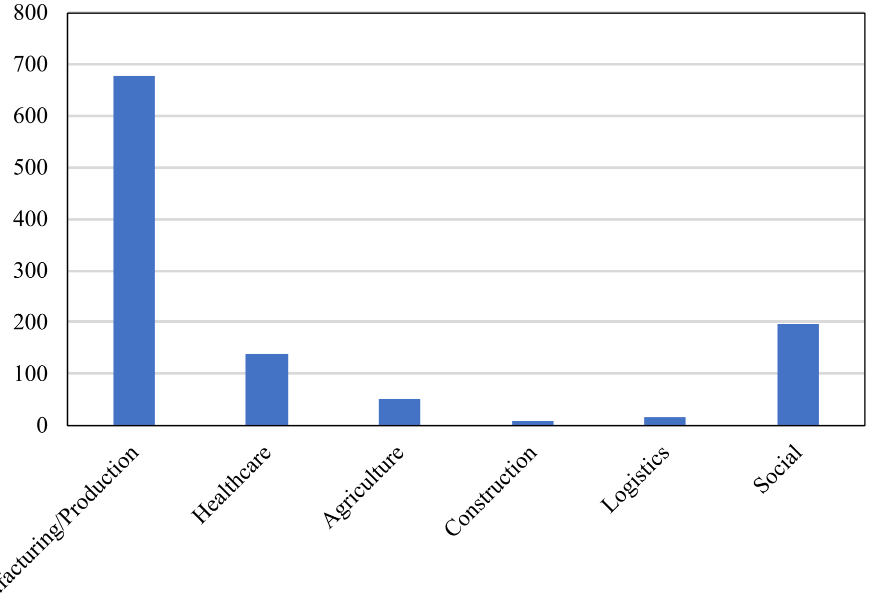

Fig. 9. Articles by application area.

complexity, lack of experience and difficulty of predicting the human behavior. Although several new approaches have been proposed in recent years to address HRC hazard analysis and risk assessment (e.g. task-oriented methods, formal verification methods, and simulation), Authors underline that a significant gap between research and industrial practices still exist. In fact, the majority of practitioners is not aware of

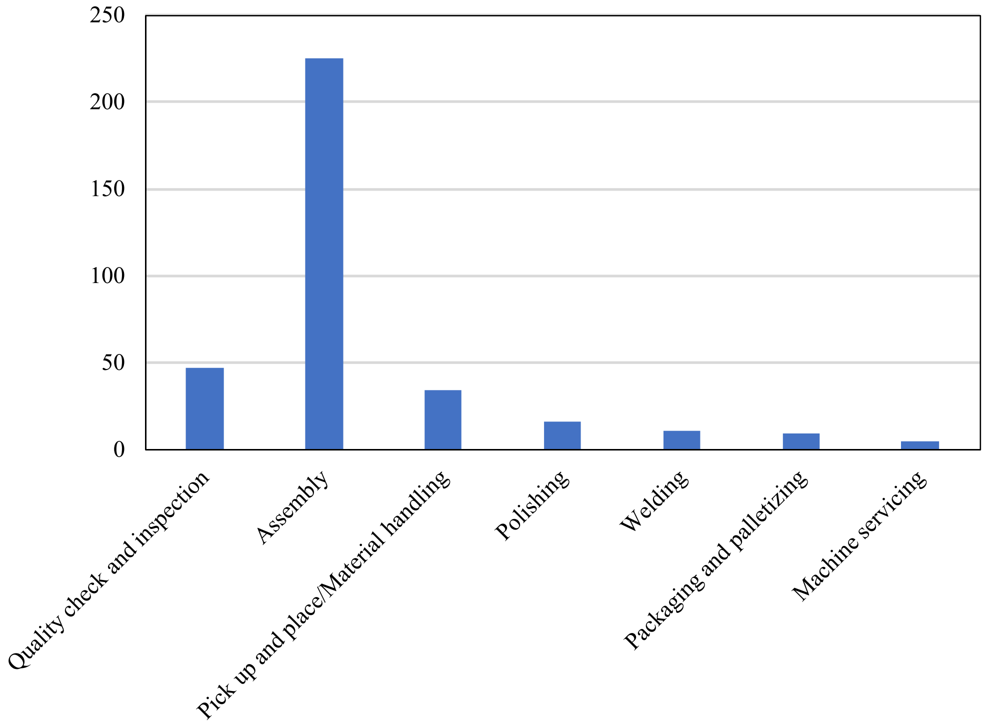

Fig. 10. Articles by robotized task.

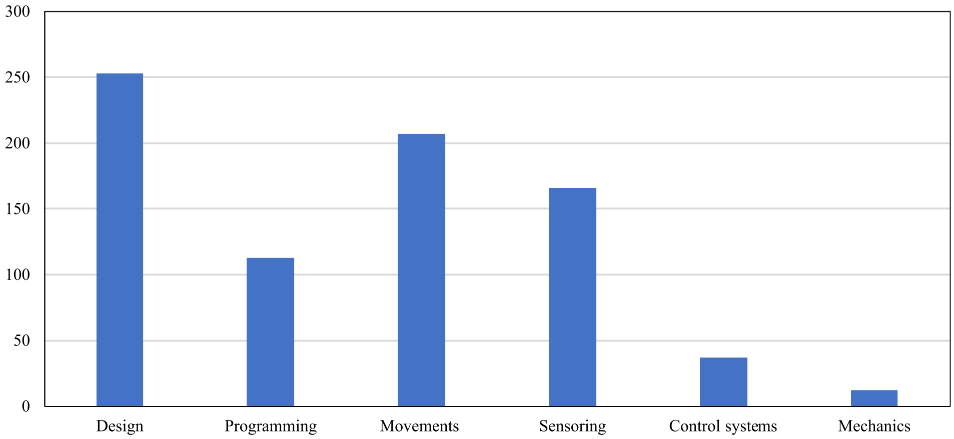

Fig. 11. Articles by technical issue.

new methods and use simple and practically-oriented approaches, often based on commercial software tools that rarely include all features in compliance with Standards. Also Hanna et al. (2022) underline that existing guidelines for hazard analysis and risk assessment are problematic as well as current regulations have a lack of focus on active safety, while merely suggesting control measures. In their work, Authors propose a novel safety management approach that allows to switch between different safety measures (e.g. visual barriers, speed limiting zones, force and torque limitations) during collaborative operations. Finally, the necessity to align human safety and systems flexibility and efficiency is stressed, also relying on education, communication and trust aspects rather than merely implementing physical measures to reduce risks. As regards the proposal of novel risk assessment methods in collaborative environments, Vicentini et al. (2020) present a methodology which relies on temporal logic language and fully automated formal verification techniques. The temporal logic-based model aims to develop the different possible ways in which tasks may be performed, while the formal verification technique is used to detect and modify hazards at early stages of the system design. Whether the estimated risk level exceeds a predefined threshold, the model highlights the need of implementing a proper risk reduction measure. Authors finally emphasize the need to embed complementary stochastic models for the human error parametrization in future researches. With relation to a multi-robot system, Bensaci et al. (2020) use the system-theoretic process analysis to identify a set of risk scenarios, while the bowtie model is proposed to assess the obtained scenarios. Based on a sample of 369 operator-injured robot accidents in Korea, Lee et al. (2021) use Systematic Cause Analysis Technique (SCAT) and Root Cause Analysis (RCA) to analyze the root and direct causes of robot accidents. Despite implementing control measures, Authors find out that the most frequent direct cause of accidents relies on the unsafe behavior of workers (e.g. access to dangerous places or parts, excessive action or movement), owing to e.g. improper physical capability and mental stress. On the other hand, robot-related accidents may also arise from system factors (e.g. narrow workspace, wrong layout, tight deadlines, absence of work standards and procedures, etc..) which make workers irritated and

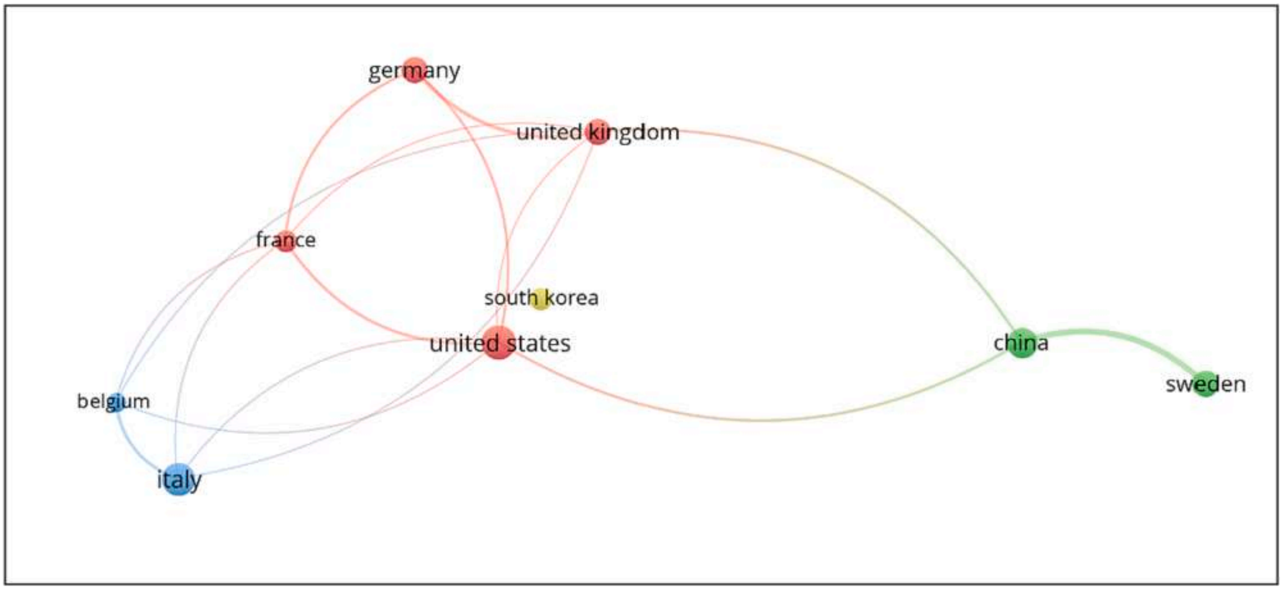

Fig. 12. Network of OHS-related documents published in Q_1 Journals by country, with co-authorship links.

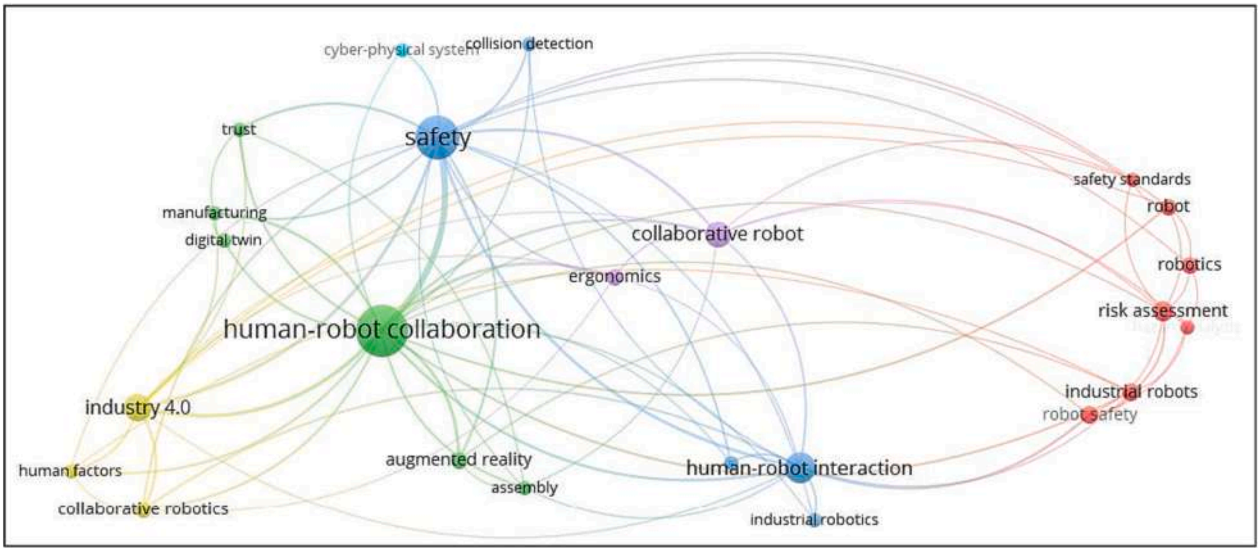

Fig. 13. Network of OHS-related documents published in Q_1 Journals by keywords co-occurrence.

impulsive. Authors finally claim that the occurrence of robot-related accidents very often arises from the omission and misevaluation of risk assessment items, which should include the human factor. Among emerging risks, Authors identify the skin hypersensitivity of operators.

3.2. *Cognitive workload and mental stress*

In HRC environments, cognitive ergonomics refers to a new branch of science which addresses to the minimization of the worker's mental stress and psychological discomfort while sharing the workplace with robots (Benos et al. 2020; Gualtieri et al., 2021). In fact, HRC is recognized to induce conditions of cognitive workload, mental stress, and frustration of workers, owing to the lack of acceptance of human beings towards the adoption of new technological solutions. Nevertheless, the human factor has been often underestimated or even ignored so far, with negative effects on both systems performance (e.g. productivity, quality) and OHS. In this regard, Villani et al. (2018) refer to the industrial sector to claim that the worker stress mainly arises from the unpredictability and high speed motions of cobot while approaching, without advance notice of motion. To reduce the mental stress and increase the worker acceptance, Authors state that HRIs based on human-centered design and cognitive engineering principles have to be considered, skipping from the perception of safety as a requirement that limits performance to the performance optimization subject to the safety constraint. You et al. (2018) employ an Immersive Virtual Environment (IVE) to analyze the worker perceived safety when performing tasks alongside a robot. Authors report that physical barriers (e.g. fence) between robots and humans used in traditional robot applications increase the perceived safety, by promoting team identification and trust in the robot. In order to reduce the mental stress, increasing the operator trust, awareness and acceptance during collaborative operations in the absence of safety barriers, IVE may be used as training tool to allow operators to familiarize with a virtual model of a robot. Nikolakis et al. (2019) implement a risk detection module within a CPS to enable the real-time evaluation of distance, also measuring the operator heart beat rate as the distance varies. Authors demonstrate that the lower the distance, the higher the

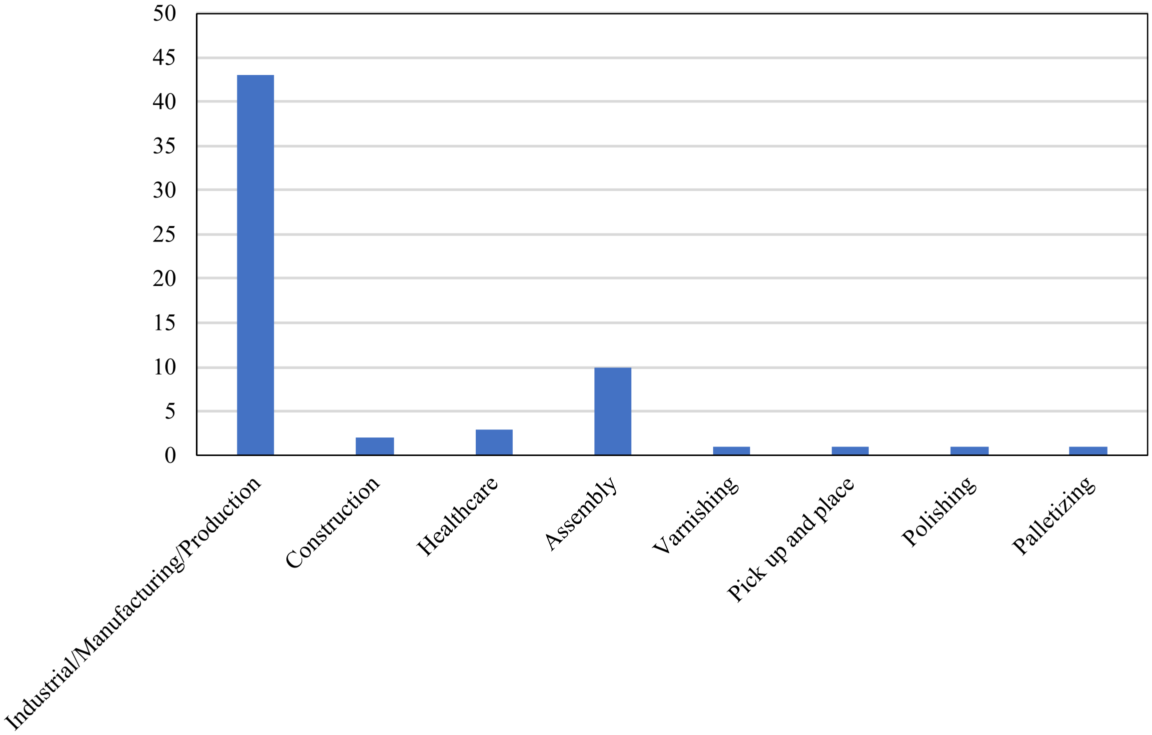

Fig. 14. OHS-related articles by application area and task.

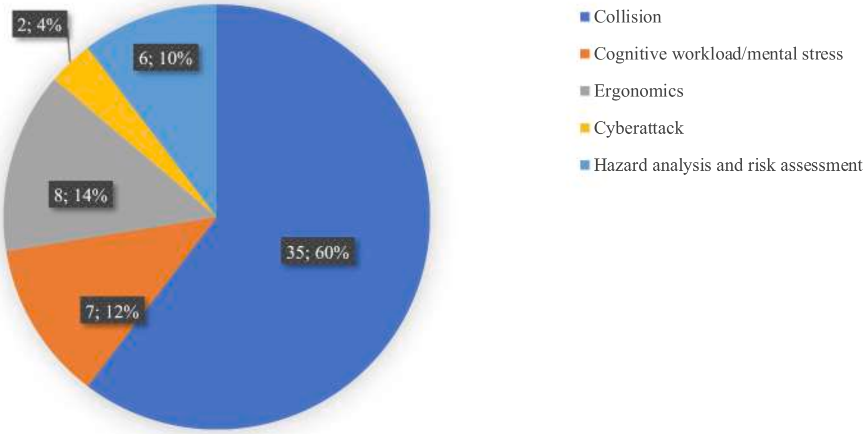

Fig. 15. OHS-related articles by research trend.

worker heart beat rate, resulting in a higher level of stress. To improve the human perceived safety, Authors claim the need to develop short response time safety systems for effective pre-impact strategies to take place in time. Oyekan et al. (2019) develop the DT of a production cell to analyze the human reaction to robot motions. Using proper human reaction-related metrics (e.g. Kinetic Energy ratio of the head and neck, acceleration of head, and so on), Authors confirm that the worker stress increases either when the robot's speed increases, the distance decreases or the operator is not aware of the forthcoming robot motions. Although the DT technology has been widely researched in the last decades, its application within robotics is still in its infancy. Owing to its potential, it hence needs to be further investigated to develop human reaction-related metrics and collaborative strategies with minimal risks. Referring to the construction sector, Liu et al. (2021a) propose a worker-centered collaborative framework to handle the cognitive load of operators. Based on brainwaves captured from a wearable electroencephalograph while the operator performs a collaborative task, his/her physiological state may be inferred, and proper adjustments (e.g. working pace) may be implemented by the robotic system. Despite confirming the feasibility of the brainwave-driven HRC, Authors underline both the need to improve the prediction accuracy of the proposed framework and to focus on the social impacts of HRC, the latter to foster aware HRIs. Gualtieri et al. (2022) define a set of possible guidelines to be implemented in the design phase of a Collaborative Assembly System (CAS), aiming to improve the cognitive response of workers. Conducted in a lab scale, the experiment reveals how the use of guidelines affect the operator frustration, trust, acceptance, perceived enjoyment, stress, and cognitive workload. As a result, Authors argue that the use of design guidelines may help technicians in developing efficient, safe, and comfortable collaborative systems. Therefore, more extensive technical documents which include psychosocial requirements for collaborative systems have to be provided in the future. To ensure the physical and psychological safety of workers during HRC, Islam and Lughmani (2022) propose a multi-layer approach to detect CPS anomalies, quantify anxiety situations, and reallocate resources (i.e. robot or human) to mitigate anxiety factors, based on a Mixed Integer Programming (MIP) model. Despite promising, the usage of machine learning techniques needs to be deepened to reinforce the proposed approach and make it smarter.

3.3. Ergonomics

Physical ergonomics deals with the physical load of workers when performing activities. It mainly focuses on effort anthropometry and biomechanics to detect wrong postures and motions that can result in musculoskeletal disorders, aiming to provide proper solutions (Benos et al., 2020). Referring to HRC, it surely allows to relieve human operators from the burden of physical-intensive tasks. In this regard, Pearce et al. (2018) define a Strain Index (SI) to quantify the hazardousness of a collaboration task under an ergonomic perspective. Based on the strain intensity and duration, hand-wrist posture, work speed and daily-shift duration, Authors demonstrate that SI is lower in collaborative operations than manual ones. Nevertheless, HRC does not avoid work-related musculoskeletal disorders, owing to e.g. to wrong postures and/or behaviors. Aiming to reduce the human effort during HRC, Roveda et al. (2020) develop a reinforcement learning-based model variable impedance controller to minimize the interaction forces in collaborative tasks, also monitoring the upper-limb activity of the worker by electromyography sensors. Safety constraints need to be also considered in future research developments to ensure the optimal control action, satisfying both the system performance and safety. In addition, AI techniques may be investigated for the automatic optimization of the model parameters. Cerqueira et al. (2020) propose a smart garment able to monitor the operator posture real-time, while a biofeedback strategy based on haptic stimulus informs the user about non-ergonomic postures, enabling safer ones. The laboratory outcomes show an overall reduction of the time percentage spent in a high ergonomic risk level, entailing postural awareness and a change and correction of posture. Although the smart garment is promising, its validation in industrial contexts has to be addressed in future works, improving wearability features (e.g. aesthetics, comfort, and weight) and investigating on the worker acceptance of the product. Referring to a collaborative polishing task, El Makrini et al. (2022) develop a postural optimization framework based on the virtual element method, contributing to lower the risk of musculoskeletal disorders. Also in this case, Authors claim the necessity to perform an in-depth study in industrial contexts, improving the technical features of the proposed framework. Gomes et al. (2022) propose a simulation-based approach to simultaneously optimize multiple ergonomic parameters. To this aim, several optimization criteria are considered, and a set of possible alternative solutions are suggested to match the user medical conditions or morphologies. By the trajectory re-planning, the proposed multi-objective optimization algorithm allows the cobot to drive the user towards more ergonomic postures when performing a joint task. Experiment outcomes are promising in respect to the ones arising from the single-objective optimization approaches already available in the literature, even if further studies have to be conducted in an industrial scale to embed the body motions optimization approach into HRC. Huck et al. (2022) develop a 3D-simulation methodology to identify hazards caused by workers' unsafe behaviors during collaboration. Starting from the generation of a set of feasible sequence of actions, Authors simulate these sequences to estimate the initial risk, and then exploit them to identify high-risk human behaviors that further increase the initial risk. Future lines of research may involve a wider range of scenarios, with more detailed human models and alternative algorithms. However, Authors highlight the complexity of simulating collaborative environments, where both expected and unexpected human behaviors have to be considered to improve the effectiveness of simulation-based tests. With relation to the healthcare sector, Prendergast et al. (2021) deal with the implementation of a medical robot for the patient shoulder rehabilitation. While a human physiotherapist only has a qualitative perception of the patient muscles strain state, the developed and tested robotic system is able to measure it, hence executing customized therapy movements that lead to lower injuries and achieve a large range of motions. The use of robot-mediated physical therapy still needs to be deepened, and further clinical studies must be carried out to evaluate and improve its efficacy, before transferring this technology to patients. The approach has to be tested on other joints and validated by more realistic multi-subject experiments (e.g. unhealthy individuals and active movements where the subject actively resists to cobot maneuvers). Nwosu et al. (2019) perform a SWOT analysis to investigate the use of medical robots for palliative, supportive care and end-of-life care. Among threats, Authors report how the use of medical robots may lead to the risk of anthropomorphizing robotic interactions, confusing the relationship between humans and robots. Societal and ethical implications of using collaborative robots in healthcare are still open issues, as well as Big Data and AI technologies in combination with robotic systems in palliative care have to be further explored.

3.4. Cyberattacks

Collaborative robotic systems consist of sensors, hardware, Information and Communication Technologies (ICTs) and human-machine interfaces. They are connected to external networks or to the internet, to exchange a huge amount of data. The latter exposes collaborative robotic systems to cyberattacks, whose consequences may range from data theft to product damage and human injuries. In this regard, Khalid et al. (2018) propose a two-step security methodology which enhances data security at key interconnected nodes and mitigates cyberattacks by a smart module for the real-time monitoring of the system security. Three dimensions of cyberattacks are considered (i.e. availability, authentication and confidentiality) and categorized based on their severity on the human safety during HRC. For future developments, Authors recommend to implement and improve IP security protocols as well as to develop suitable design guidelines to guarantee the security of complex multi-degree collaborative CPSs. With relation to an assembly line, Khalid et al. (2022) simulate a cyberattack to demonstrate the effect of a compromised robot on the worker safety. Authors underscore the necessity to integrate safety and security issues in future design of collaborative CPSs, systematically identifying hazards and subsequent risks. Aiming to ensure a safe collaboration even in the case of compromised layers, control systems and mitigation plans able to promptly detect and mitigate cyberattacks respectively are also paramount.

3.5. Collisions

Among the selected list of articles, the majority of contributions on OHS-related issues in HRC deals with the risk of collision, owing to the absence of physical barriers between humans and robots while sharing the workspace. Collisions may arise from a wide variety of unpredictable reasons (e.g. incorrect programming of cobot movements, unsafe worker behavior, and malfunctioning of safety measures), which potentially result in human injuries of different severity. In this regard, an exhaustive list of potential injury threats due to collisions is summarized in Haddadin et al. (2008). Thus, the design of proper safety measures is paramount for researchers and practitioners to avoid collisions or immediately mitigate their effects (e.g. stopping the robot whether the collision already occurred). While the collision avoidance pre-empts dangerous contacts, the concept of contacts detection and mitigation is based on the reduction of the collision energy (Gualtieri et al., 2021).

In the following two sub-sections, articles focused on collisions avoidance and on collisions detection and mitigation are reviewed respectively.

3.5.1. *Collision avoidance*

Two main collision avoidance safety strategies are reported in the literature, i.e. robot stop/slowdown and trajectory re-planning. The first strategy very often involves the use of sensors designed to monitor the worker position, promptly stopping or slowing down the robot to avoid collisions. While ensuring the worker's safety, it increases the completion time of tasks assigned to the cobot (Ragaglia et. al., 2018). Instead, the robot trajectory re-planning represents a trade-off strategy between safety and completion time.

Aiming to better detail and identify collision avoidance research subjects, reviewed articles are categorized in the following sub-sections.

3.5.1.1. Trajectory monitoring and re-planning. Savazzi et al. (2016) propose the use of wireless device-free localization methods and architectures to detect the worker position in a collaborative workspace. In particular, the worker position and motion are estimated by the radio wave perturbations induced by the human body, based on devices installed in peripheral locations of the plant. As a result, the worker is not equipped by neither wireless active devices nor specific tracing sensors, and the estimated worker position can be used for the generation of a dynamic trajectory-dependent algorithm around either the robot or the operator. Referring to an assembly cell, Cherubini et al. (2016) combine trajectory optimization, admittance control, and image processing to reduce the risk of collision, while also diminishing the human strain injuries. Kim et al. (2016) use the manipulator safety index to evaluate the risk of collision during the human interaction with an articulated manipulator. Using the redundant degree of freedom which characterizes the manipulator, the posture of the robot (e.g. elbow-down, elbow-up) may be modified without deviating the end-effector position from the given trajectory, which results in a lower risk of collision. Unhelkar et al. (2018) integrate a human motion prediction model with a path planner into the so-called CobotSam system. To avoid collisions, the prediction model allows the estimation of the human's long-term path, whereas the path planner is used to adapt the subsequent robot motion. Experiments run in a BMW® test environment and result in fewer safety-related stops, shorter task completion times, and improved measures of interaction's fluency. Ragaglia et al. (2018) develop a trajectory generation algorithm that maximizes productivity (i.e. preventing task interruption) while considering safety as optimization constraint (i.e. avoiding collisions with the worker). By depth sensors, the algorithm receives input data on the worker position and speed, whereas a novel strategy to predict the worker space occupancy is developed. As a result, the manipulator trajectory is reactively modified in respect to the pre-programmed path, in order to satisfy the minimum separation distance constraints. With relation to a sanding operation, Maric et al. (2020) combine the Safety – rated Monitored Stop (SMS) and Speed and Separation Monitoring (SSM) functions to gradually reduce the robot speed until the final stop, when the operator enters the work area and approaches the cobot. Liu et al. (2021b) present a deep reinforcement learning approach for the real time collision-free motion planning of an industrial robot, in the attempt of making the robot able to self-learn how to reduce risks while ensuring the task completion. Starting from the formulation of the problem as a Markov decision process, a specifically reward mechanism is designed to guide the robot to learn the expected behavior. Since deep reinforcement learning and intelligent robotics are still at the cutting-edge of the artificial intelligence research, future works may focus on the investigation of higher dimension and amount of data, generalization to more complex scenarios, experiments with real physical robots based on enhanced sensing methods, advanced reward function integrating with smooth control, and new theories and algorithms customized for industrial tasks. Also Zhao et al. (2021) present a reinforcement learning algorithm with a hazard estimator to ensure the human safety while not sacrificing the task efficiency. In particular, the proposed method allows the robot to avoid humans without interrupting its own workflow, by a hazard evaluation based dynamic goal selection. In the offline training phase, the control policy and the hazard estimator are trained so as the robot learns to get a static goal, avoiding workers. On the other hand, a guidance goal along a given task path is dynamically changed in the testing phase, to guide the robot switching between following the path and avoiding workers. The self-capacitive-based technology is used by Gbouna et al. (2021) to design a skin proximity sensor which enables the cobot with an extended sense of touch, allowing approach and contact measurements. Two collaborative modes are investigated. The first one (i.e. interaction mode) utilizes the ability of the sensor to localize the action point, so that the gesture command is used for the robot manipulation. In the second mode (i.e. safety mode), the sensing robot skin continuously measures the proximity between robot and dynamical obstacles, enabling the robot to dynamically modify its trajectory to avoid collisions. Demirtas et. al (2022) propose a path adaptation algorithm and an AR-based warning system to enhance worker safety conditions while minimizing the production delay. Unlike many algorithms in the literature require additional interventions to the closed control architecture of the industrial robots, the proposed algorithm may be implemented as a custom movement function available to users. Further studies may be conducted to better adapt the system to real robotic cell, also incorporating additional sensors to improve the detection capability, response time, and comprehensiveness. Faroni et al. (2022) develop a proactive trajectory planner which focuses on the path execution time minimization, while considering robot stops and slowdowns in case of human proximity to either avoid or mitigate the potential contacts. Authors claim that further research efforts are needed to decrease the computational time to run the algorithm.

3.5.1.2. Safety zones monitoring. Wang (2015) presents a 3D model based on real sensors data and depth images of the human operator for the web-based real-time monitoring and remote control of a robot. To avoid collisions, the robot is stopped or moved away when the operator is approaching. Besides the necessity to test the model on a more complex system, the human, environmental and economic sustainability of HRC need to be further studied. Mohammed et al. (2017) combine virtual 3D robot models and depth cameras for the real human operator images processing. Depending on the operator proximity, four safety avoidance strategies are implemented (i.e. operator alert, robot stop, distancing the robot, or trajectory re-planning) to detect and avoid collisions. Kimmel and Hirche (2017) present a novel control scheme for human–robot interaction, which enforces dynamic constraints even in the presence of external forces. Based on an analytic constraint description and a feedback linearization of the system dynamics, a safe set of states is determined, which is then rendered controlled positively invariant, thus keeping the system in a safe configuration. Based on a primary 3D simulation, Michalos et al. (2018) reproduce an assembly automotive cell in a lab scale to analyze all aspects of HR interactions. While AR glasses are used to visualize information on both the robot and task execution status, smartwatch interfaces are employed to give instructions to the robot during the manual guidance collaborative mode. In accordance with the European Standards, SMS, SSM and Power and Force Limiting (PFL) safety strategies are adopted to avoid or mitigate the risk of collision respectively. Based on experiments, Authors underline the need of both more advanced sensing capabilities for collision detection and avoidance during close cooperation and standardized services to integrate all the heterogeneous sensing and interaction technologies. Using a virtual reality environment, Matsas et al. (2018) examine two safe collaboration techniques to foster the worker situational awareness and anticipation behavior during collaboration. In the first technique (i.e. proactive), the worker is supposed to be equipped by audiovisual aids by means of which e.g. visualizing the cobot area and receiving an alert of proximity. By the proactive technique, the robot also decelerates when the forthcoming contact with the user is traced. The second technique, named adaptive, is targeted on the cobot, which retracts and moves to the final destination via a modified trajectory if the minimum safe distance is exceeded, so avoiding the worker. Alternative ways to transcribe the application from a virtual to a real environment are still open research issues. Based on a 160-GHz radar MMIC, Geiger and Waldschmidt (2019) present a close range proximity sensor with flexible antennas to monitor the cobot workspace. The proximity sensor allows to reduce the number of sensors embedded into the system, to cover a wide danger area and to detect the expected targets (e.g. body parts) by stopping the robot. Further studies may concern the combination of several sensors around the robotic arms, also determining the target position by a different approach instead of multilateration. Instead of a safety passive system, Hietanen et al. (2020) present a dynamic AR-based interaction model for HRC. It is based on both a depth-sensor for the workspace monitoring and an interactive AR user interface. While the operator can freely move within his/her zone, the robot zone is dynamically changed based on tasks to be performed as well as the robot is stopped if the operator, or any other object, enters the robot zone. Future experiments may include the usage of the latest generation of Microsoft HMD (HoloLens 2), owing to its improved technical, visual, and functional features. Ko et al. (2021) develop a CPS environment where worker-equipment collisions are detected in advance to ensure safety. A depth-image camera is installed outside the equipment, while an internal autonomic control process is devoted to determine safety strategies to avoid expected worker-robot collisions, the latter resulting from a simulation module. Nevertheless, the reliability of CPS may be compromised by the temporal and physical position errors that may occur in the simulated environment. Therefore, additional axis feedback sensors are required to increase the accuracy of CPS, also considering the worker body shape and the number of simultaneous workers. Tong et al. (2022) enhance the robot arm by an ultrasonic proximity sensing skin, able to detect obstacles. Even if highly promising to improve the control ability of robots, the experimental results underline the need of further studies to optimize the widespread use of the sensing skin. Scalera et al. (2022) propose the online scaling of dynamic safety zones to increase the fluency and productivity of HRC. The approach works towards the minimization of the time of potential stop trajectories, considering the robot dynamics and torque constraints. Alternative optimization strategies to minimize the stop time and the trajectory generation subjected to kinematic and dynamic constraints may represent further research developments. Fraga-Lamas et al. (2022) present a Cyber-Physical Human-centered System (CPHSs) that enables increased operator safety and operation tracing in manufacturing HRC processes. Aiming to monitor the human proximity to avoid contact situations in industrial scenarios, a hybrid edge computing architecture is combined with low-cost thermal imaging sensors. Specific guidelines are also provided to support future CPHSs developers and managers, fostering the development of smart and sustainable manufacturing. Zhang et al. (2022) develop a dynamic human-robot fusion algorithm to estimate real-time the minimum human-robot distance, based on image processing and 3D representation. As a result, the robot path is promptly adjusted to ensure a safe and efficient collaboration.

3.5.1.3. Safety distance monitoring. Costanzo et al. (2022) merge fuzzy inference and sensor fusion algorithms to control the robot velocity, simultaneously enforcing the system safety and productivity. Images acquired from different depth sensors along with the ones arising from a thermal camera are treated by the sensor fusion algorithm, by using a machine learning approach. Li et al. (2022) claim the difficulty and the low accuracy of current humans-robots distance measurement approaches. Therefore, Authors focus on the pre-collision stage to develop a control framework based on DT, which allows to promptly and accurately measure the minimum safe distance between humans and robots. As a result, different safety robot strategies are adopted to avoid contacts. However, data transmission and processing capabilities have to be improved in future studies, as well as sudden and moving obstacles in the surrounding environment need to be properly managed as potential causes of collisions. Zanchettin and Lacevic (2022) present a real-time methodology to guide a robotic manipulator alongside an assigned path, simultaneously optimizing productivity (i.e. minimum time of completion) and safety according to the SSM strategy of ISO TS 15066. Lee et al. (2022) formulate and solve a mathematical programming model for the optimal planning and assignment of disassembly tasks among the worker, the robot, and HRC. The objective function to be minimized is the total disassembly time, subject to resources and safety constraints. As concerns the safety constraints, a minimum safety distance requirement is forced to avoid human injuries and possible collisions during disassembly.

3.5.2. Collision detection and mitigation

Ren et al. (2018) combines the robot dynamic model along with the Modified Extended State Observer (MESO) algorithm for a fast and robust collisions detection, moreover providing information on magnitude and direction of force signals arising from a general class of actuator faults. MESO overcomes the need to estimate acceleration and is robust to torque disturbances, which result into an accurate residual estimation. Based on the estimated residual, proper collision reaction strategies are to be deepened in future works, and uncertainties need to be included in the robot model to enhance its flexibility. Papanastasiou et al. (2019) introduce a suite of software and hardware components that allows the aspired seamless HRC scheme. Perception technologies and wearable devices are combined to assist the operator and increase his/her awareness, also embedding the system with safety functionalities to detect collisions (e.g. safety skin and safety monitored regions delimiting the area of the robot activities). Future works are still required to focus on the integration of heterogeneous sensing and interaction equipment, also including the new available safety measures into design and planning tools that can efficiently simulate their effect on manufacturing processes. Owing to the expensiveness of sensors used to acquire the force interaction information, Xiao et al. (2021) refer to a CAS to propose a load and friction compensation method which avoids the usage of additional force and torque sensors. An impedance control algorithm is also used to adapt the robot to task demands and to make it compliant to limit the collision force. Enhanced robot safety and flexibility are proved by the experimental results, indicating a great potential for industrial applications. In future works, model-free methods based on reinforcement learning and transfer learning have to be investigated to train robots, in the attempt of making them more similar to human arms and adaptable to different task scenarios. Pang et al. (2021) combine multiple soft sensors into a robot skin (i.e. CoboSkin) to reduce the impact force during collisions by a variable robot stiffness. CoboSkin is also characterized by a modular design which allows to adjust its sensing function, stiffness and size to the robotic structure. In future studies, the rectangular shape of CoboSkin basic units should be further investigated, and its structure design should be optimized, e.g. adopting materials with higher strength and utilizing 3D printing technology. Since the importance to promptly detect and mitigate collisions, Zhang et al. (2021) design an online Collision Detection and Identification (CDI) scheme which makes use of supervised learning algorithms and Bayesian decision theory. CDI is able to identify collisions within 20 ms, also distinguishing between intentional and accidental collisions. As a result, appropriate collision mitigation strategies may be promptly implemented. CDI runs on a specific robot platform, which also includes data collection, feature engineering, and model training. Thus, different platforms need to be investigated to spread the CDI scheme. Future studies may also address to both the effects compensation for varying robot loads and the individual uncertainties influence on the collision classification accuracy.

Based on the definition of acceptable force thresholds as collision mitigation strategy during collaboration, Park et al. (2019) evaluate the pressure pain thresholds for collisions, under the assumption that they are lower than the mild injury threshold. Thresholds for pain onset and maximum bearable pain based on clinical trials are evaluated by Han et al. (2022). In their study, Authors aim to clearly establish biomechanical limitations as robot collision safety criteria. Using the pain onset rather than the maximum bearable as safety criterion to generate safe trajectories, a higher HRC productivity is expected with relatively diminutive risk. With relation to the automotive sector, Gopinath et al. (2021) present a laboratory demonstrator to deal with the hazards analysis and risk assessment in assembly operations of plastic panels on a continuous line. The most critical risk identified by the Authors relates to collisions, and proper risk reduction measures are hence designed (e.g. laser scanner to monitor the collaborative workspace, blunt corners and soft-padding, force sensors to stop robot motion).

3.5.3. *Limitations*

The main limitations of the implemented research methodology are given in the following.

- Owing to the large amount of documents in the field of HRC safety, it was both advantageous and necessary to rely on a limited number of documents in the attempt of focusing only on the ones deemed to meaningfully contribute to answer the stated research questions. Therefore, the literature review was based on articles published in journals of the first quartile. According to the common practice of the academic research community, the journal quartile was hence used as objective quality criterion of a scientific publication, and Q1 journals were considered as the most prestigious and relevant ones. On the other hand, diverse Quality Assessment (QA) tools have been in use in medicine and sociology studies to assure the reliability of findings and conclusions, based on the quality of the selected primary documents (Yang et al., 2021). While QA instruments are mature in the disciplines of medicine and sociology, there is a need to develop and enforce their usage in the other research fields when performing a systematic literature review (Ali and Usman, 2018). Therefore, to enlarge specific aspects emerged by the conducted literature review, a possible future development of the present study might certainly concern its extension to articles published in conference proceedings and book series, also considering journals of different quartiles. In addition, a proper QA assessment tool could be implemented to assure consistent and robust results.
- Even if mentioned within the manuscript, grey literature in the area of HRC was not considered to conduct the bibliometric analysis and the literature review. Although the search, access, and evaluation of grey literature may be difficult, its inclusion could meaningfully enrich the review and its outcomes, mainly with relation to industry-related documents.
- The outcomes of the performed analysis were categorized based on RQs, also in the attempt of facilitating the reader in navigating the paper. Other researchers could obviously define a different categorization.

4. Discussion

In response to RQ_1 and RQ_2, the major outcomes drawn from the performed bibliometric analysis and literature review are hereafter discussed and synthetized in Table 1, in the attempt of suggesting either new or deepened lines of research in the area of OHS in collaborative environments. Although the industrial automation was introduced by the third industrial revolution, robotic applications and the consequent HRC paradigm have been mainly developed since 2011 (Fig. 3), which actually and uniquely identifies the beginning of Industry 4.0. Accordingly, the bibliometric analysis and the literature review described in the previous sections emphasize the central role played by the key enabling technologies of Industry 4.0 (e.g. DT, AR, AI, cloud, etc..) (Fig. 8) in designing and developing inherently safe collaborative solutions. It is noteworthy, and also obvious, how HRC-related issues are mostly investigated in industrialized countries (Figs. 4 and 6), where the introduction of more and more advanced technologies allows to increase not only the independence of workplaces from humans, but also to make them safer. Nevertheless, this scenario suggests how the impact of the fourth industrial revolution might widen the gap between industrialized and developing countries in the next years. Among the robotized tasks (Fig. 10), the majority of the studies deal with the assembly, owing to the potential of automation to eliminate low ergonomic workstations and to increase the system productivity by the reduction of manual activities with no added value.

Although the overall safety of collaborative modes has increased over time, various safety concerns still need to be faced to allow humans to operate alongside robots without safety barriers, as in traditional robot applications. In this regard, the performed systematic literature review aims to find out the latest updates and open challenges on OHS in collaborative environments, aiming to bring improved benefits over the state of the art. Five main areas of study are identified, namely hazard analysis and risk assessment; cognitive workload and mental stress; ergonomics; cyberattacks; collisions. As concerns the first area, technologies that make up robotics are more and more complex and increase the likelihood of unpredictable risks, mainly due to the human factor. Accordingly, reviewed articles highlight the need to align the safety level and the systems performance, while integrating personal aspects of workers into the hazard analysis and risk assessment phases. Despite the available Standards recognize the paramount role of hazard analysis and risk assessment to appropriately implement safeguards in collaborative environments, the provision and/or revision of more specific guidelines seem to be desirable to best suit the collaborative context. In addition, a significant gap between research and industrial practices emerges prominently, so that academics should actively assist industries to make them aware of novel and enhanced methods addressed to the hazards identification and the risks prevention and/or mitigation.

As concerns the area of cognitive workload and mental stress, the number of studies focused on the workers' acceptance is low, being the acceptance a concept that returns a measure of the understanding and trust degree of human beings towards the adoption of new technological solutions. Owing to the impact of the emotional state on the worker exposure to risks, monitoring the human behavior and reaction is fundamental, providing proper metrics and tests to evaluate and mitigate his/her discomfort while sharing activities and workspaces. As a result, cognitive ergonomics represents one of the most promising research challenge to design and develop human-centered robotic systems, based on cognitive engineering principles to minimize the work-related psychosocial risks. Further studies may concern the use of enabling technologies (e.g. AR, machine learning and IVE) and the development of appropriate measures (e.g. training and design guidelines) and metrics to assess and promptly manage stressful situations, increasing the worker awareness, trust and acceptance. While cognitive ergonomics is in its early stage, physical ergonomics has been widely investigated in the literature, also in HRC (Benos et al., 2020; Gualtieri et al., 2021). Among others, multi-objective optimization algorithms and enabling technologies (e.g. simulated environments), combined with both the robot trajectory control and the usage of smart work garments to monitor and correct the worker's posture, have been proposed. However, further studies are needed to enable their transfer to the industrial scale as well as to develop novel methodologies to decrease the operator's workload, mainly based on his/her physical conditions (e.g. anthropometric features, age, gender, disabilities, etc..). The latter will obviously require the usage of a considerable amount of data about the worker's physical conditions.

From the literature, it is also noteworthy how the increasing level of automation exposes industries to cyberattack threats, which may result in data theft, product damage and human injuries. As a result, proper guidelines and protocols to prevent dangers inherent in the network and to hinder cyberattacks need to be developed, integrating safety and security issues in the design of collaborative systems. Studies show that businesses can be vulnerable to sophisticated attacks based on e.g. AI

Table 1
OHS in HRC environments.

HRC-related concerns	Findings	Future trends of research	Application area (lab or shop floor)	Reference
Hazard analysis and risk assessment	→Lack of focus on proper hazard analysis and risk assessment methodologies →Lack of focus on human factorsmonitoring and optimization by →Gap between research and industrial practices	→Specific and human-centered guidelines for the hazard analysis and risk assessment in HRC environments →Update of safety Standards to align the safeguards design and the outcomes of the hazard analysis and risk assessment →Transferring new HRC-related hazard analysis and risk assessment methodologies from researchers to practitioners	Multidisciplinary	Chemweno et al., 2020
			Assembly in a flexible manufacturing system	Vicentini et al., 2020
			Multidisciplinary	Huck et al., 2021
			Automotive industry (lab)	Hanna et al., 2022
			Industrial/ Manufacturing/ Production (lab)	Lee et al., 2021
Cognitive workload and mental stress	Lack of human trust, awareness and acceptance during collaborative operations, owing to the cobot proximity, unpredictability and high speed motions	→Human–Robot Interfaces (HRIs) based on human-centered design and cognitive engineering principles →Enabling technologies (e.g. IVE, DT, ML, etc..) and smart wearable devices (e.g. garment, glass, etc..) for the real-time monitoring of human-reaction related metrics to improve the perceived safety →Technical guidelines - also including psychosocial requirements - to be used in the design of more efficient, safe, and comfortable collaborative systems	Industrial/ Manufacturing/ Production	Villani et al., 2018
			Assembly, Automotive industry (lab)	Islam and Lughmani, 2022; Nikolakis et al., 2019
			Assembly (lab)	Gualtieri et al., 2022
			Construction (lab)	Liu et al., 2021a; You et al., 2018
			Industrial/ Manufacturing/ Production (lab)	Oyekan et al., 2019
Ergonomics	→Musculoskeletal disorders due to unsafe worker postures →Anthropomorphizing robotic interactions	→Real-time postural monitoring and optimization by e.g. smart garments, virtual element-based frameworks, multi-objective optimization approaches, and 3D-simulation to be further deepened in industrial contexts →Motion planning and control and task scheduling strategies based on e.g. reinforcement learning-based models to minimize the interaction forces in HRC tasks →Economic, societal and ethical implications of using HRC in the healthcare sector	Industrial/ Manufacturing/ Production	Pearce et al., 2018
			Industrial/ Manufacturing/ Production (lab)	El Makrini et al., 2022; Huck et al., 2022; Roveda et al., 2020
			Generic tasks containing different working postures; Multidisciplinary (lab)	Cerqueira et al., 2020; Gomes et al., 2022
			Healthcare (lab)	Nwosu et al., 2019; Prendergast et al., 2021
Cyberattack	Threats of data theft, product damage and human injury	→Guidelines and protocols to integrate safety and security issues in the design of collaborative systems →Systematical identification of hazards and risks in case of worker exposure to a compromised robot	Industrial/ Manufacturing/ Production (lab)	Khalid et al., 2018, 2022
Collision	→Complexity and expensiveness of sensors (e.g. long range sensors, DFL, depth sensors, etc.) →Feedback errors caused by the excessive sensitiveness of current detection systems →Prolonged task completion times in stop/slowdown strategies →Challenging simulation of the worker behavior, owing to the human unpredictability and variability	→Enhanced sensing capabilities and integration of heterogeneous sensing equipment →Effective pre-empting strategies to take place in time, shortening the safety system response time (e.g. optimal strategies to predict the worker space occupancy to reactively modify trajectories) →3D modeling and depth imaging in augmented reality environment to effectively detect collisions →Robots training by model-free methods based on reinforcement learning and transfer learning, tested on higher amount of data and generalized to more complex scenarios →Improved robot sensing skin (e.g. material optimization) for obstacles detection →Effective simulation-based tests, also covering human deviating behaviors →Power and force limits for various parts of the human body to avoid injury and/or pain from different types of contact between the robot and the worker	**Collision Avoidance**	
			Assembly (lab)	Cherubini et al., 2016; Hietanen et al., 2020; Li et al., 2022; Unhelkar et al., 2018; Wang, 2015
			Assembly, Automotive industry	Michalos et al., 2018
			Industrial/ Manufacturing/ Production (lab)	Geiger and Waldschmidt, 2019; Tong et al., 2022; Scalera et al., 2022; Matsas et al., 2018; Zhao et al., 2021; Kim et al., 2016; Mohammed et al., 2017; Ko et al., 2021; Fraga-Lamas et al., 2022; Faroni et al., 2022; Liu et al., 2021b
			Sanding operation (lab)	Maric et al., 2020
			Handling and assembly tasks (lab)	Savazzi et al., 2016
			Industrial/ Manufacturing/ Production	Costanzo et al., 2022
			Palletizing, Industrial/ Manufacturing/ Production (lab)	Demirtas et al., 2022; Zanchettin and Lacevic, 2022
			Multidisciplinary (lab)	Kimmel and Hirche, 2017; Ragaglia et al., 2018
			Multidisciplinary; Robot maintenance (lab)	Zhang et al., 2022
			Disassembly (lab)	Lee et al., 2022
			Healthcare (lab)	Gbouna et al., 2021
			Collision detection and mitigation	

(*continued on next page*)

Table 1 (*continued*)

HRC-related concerns	Findings	Future trends of research	Application area (lab or shop floor)	Reference
			Assembly (lab)	Papanastasiou et al., 2019; Xiao et al., 2021
			Assembly; Automotive industry (lab)	Gopinath et al., 2021
			Industrial/ Manufacturing/ Production	Pang et al., 2021
			Industrial/ Manufacturing/ Production (lab)	Zhang et al., 2021; Ren et al., 2018; Park et al., 2019; Han et al., 2022

and machine learning, owing to their ability to bypass the defense systems. However, the same enabling technologies may be used to detect and respond to threats more effectively, so that further research efforts are expected in this direction. The systematical identification of hazards and risks in case of workers' exposure to a compromised robot need to be also deepened.

Finally, collision is the most researched issue. In this regard, the analyzed papers show that the frequency and duration of exposure to collaborative movements increase the possibility of collisions, and thus the likelihood of worker injuries. Accordingly, the use of more and more advanced technologies (e.g. depth-image processing and 3D modeling), able to enhance the detection capabilities and to shorten the response time of safety measures, is challenging to design low-risk HRC systems while ensuring the system productivity. Likewise, the study of more complex scenarios, characterized by a significant amount of data, may lead to a further refinement of machine learning techniques associated with safety systems. However, the lack of unified data sets for training and generating real data in machine learning applications is currently a further compelling challenge to foster the incorporation of machine learning into safety (Zacharaki et al., 2020; Mukherjee et al., 2022). Also the modelling of the human behavior unpredictability may provide an interesting research insight, based on techniques such as simulation and AI. Preventing human-robot contacts in collaborative operations, reducing the risk to zero, is obviously impossible, and physical contacts are no longer excluded but allowed and regulated by the principle of limiting the effect on the human body. Despite that, few studies identify the collision threshold, which needs more investigations and deep study to establish biomechanical limitations as robot collision safety criteria.

The present work confirms that HRC has mostly involved the industrial context so far (Fig. 9). On the other hand, service robots for personal use and robots addressed to the healthcare sector are still far from reaching their economic potential. Certainly, robotics has a number of possible applications in e.g. household chores, palliative, supportive and end-of-life care, but its employment in a natural environment inhabited by humans requires precise requirements concerning sensory perception, mobility and dexterity as well as the ability to plan tasks, make decisions and carry out reasoning. Therefore, deepened and specific studies are still required to investigate the social and ethical implications of HRC.

Under the industrial perspective, the analysis conducted underlines the further need to align research agendas and practical needs of industries, as also confirmed by the technical reports of the European Union (EASFW, 2023; EPRS, 2023). On the one hand, the ever-increasing availability of more competitively priced and flexible cobots acts as a driver for the company's automation and offers several opportunities. On the other hand, HRC often meets barriers from both the employees and management perspectives, especially in Small and Medium Enterprises (SMEs) (Kopp et al., 2021; Richert et al., 2018, EASFW, 2023; EPRS, 2023). In this regard, HRC deployment in industrial environments is limited by both the high investment cost and the need to incur in new investments to keep up with the technical evolution. In addition, the use of cobots require continuous training activities of workers that perform collaborative tasks and of programmers, to avoid people injuries and system malfunctions. Also the European reports emphasize the central role of the human-factor, which cannot be neglected in robotics applications to increase the worker acceptance and trust. To this aim, companies might benefit from the exchange of information and the collaboration with stakeholders that have already implemented similar solutions.

5. Conclusions

The global market of cobots is projected to exponentially increase in the next years, owing to the huge potential of HRC to integrate the industrial automation advantages with the unique cognitive skills of the human being. More flexible, efficient, and sustainable production systems as well as improved worker conditions are potentially enabled by robotics. Nevertheless, the complexity and variety of automation technologies as well as the human unpredictability lead to new hazards and risks in collaborative environments, which result in new challenges in the area of OHS. Therefore, the present work presents a bibliometric analysis and a literature review, with the aim of providing an extensive overview of the state of the art on OHS-related concerns and solutions, also investigating the most researched topic and application areas of HRC. Possible lines of research are derived as a result.

The future of HRC unavoidably requires further investigations, mainly dealing with real contexts besides lab applications. In this direction, safety constraints need to go at the same pace as systems performance requirements, abandoning the perception of safety as a performance-limiting factor. The latter is paramount to foster the development of collaborative systems, from a lab scale to a shop floor.

CRediT authorship contribution statement

Antonio Giallanza: Conceptualization, Methodology, Writing - original draft, Investigation, Project administration. **Giada La Scalia:** Conceptualization, Writing - original draft, Supervision, Software, Validation. **Rosa Micale:** Conceptualization, Writing - original draft, Supervision, Software, Validation. **Concetta Manuela La Fata:** Conceptualization, Methodology, Supervision, Writing - review & Editing, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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