Robotics and Computer Integrated Manufacturing 67 (2021) 101998

Contents lists available at ScienceDirect

Robotics and Computer Integrated Manufacturing

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

Review

Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review

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ARTICLE INFO

Keywords:
Industry 4.0
Collaborative robots
Human–robot collaboration
Safety
Ergonomics
Human factors
Systematic literature review

ABSTRACT

Human–robot collaboration is a main technology of Industry 4.0 and is currently changing the shop floor of manufacturing companies. Collaborative robots are innovative industrial technologies introduced to help operators to perform manual activities in so called cyber-physical production systems and combine human inimitable abilities with smart machines strengths. Occupational health and safety criteria are of crucial importance in the implementation of collaborative robotics. Therefore, it is necessary to assess the state of the art for the design of safe and ergonomic collaborative robotic workcells. Emerging research fields beyond the state of the art are also of special interest. To achieve this goal this paper uses a systematic literature review methodology to review recent technical scientific bibliography and to identify current and future research fields. Main research themes addressed in the recent scientific literature regarding safety and ergonomics (or human factors) for industrial collaborative robotics were identified and categorized. The emerging research challenges and research fields were identified and analyzed based on the development of publications over time (annual growth).

1. Introduction

The current evolution in industry is commonly defined through the ‘Industry 4.0′ concept [1]. Human-machine interaction (HMI), in particular human–robot collaboration (HRC), is a main cyber-physical and enabling technology of Industry 4.0 [2].

HRC is one of the so called nine key technologies according to the widely used classification of Boston Consulting [68] together with: additive manufacturing, augmented reality, vertical and horizontal data integration, simulation, cyber security, industrial internet of things, big data analytics and cloud computing.

Industrial collaborative robots are a category of robots that perform tasks in collaboration with workers in industrial settings [3]. In other words, collaborative robotics is introduced to help operators perform manual activities and allows a safe physical interaction (direct or mediated) between humans and machine systems. The final goal is to improve production systems performance and operators work conditions by matching typical machine strengths with human inimitable skills [4]. Collaborative systems can provide many advantages but also challenges in terms of physical human–robot interaction (HRI). In fact, ensuring safety and ergonomics (or human factors) of operators in a hybrid workspace during shared operations could be complex. Actually, a collaborative system is designed for interaction with a human within a defined collaborative workspace where the main hazard category will be of mechanical type. This is because it is possible to have potential not-functional (and unwanted) contacts between the human and the robot during the sharing of the workspace. While collaborative robots present some inherent safety measures which allow the implementation of safe applications, this state usually changes as soon as they are integrated into a working environment and equipped with different types of end-effectors. For this reason, safety systems for collision avoidance and/or contact mitigation as well as safety measures related to the workcell design must be adequately implemented.

Ergonomics (or human factors) involves the psychophysical and social wellbeing of operators. From a physical point of view, collaborative robots can facilitate a reduction of biomechanical overload by supporting operators in heavy and repetitive tasks. On the other hand, a close collaboration could provide psychological stress to operators. In fact, operators’ wellbeing and performances can suffer from the unknown robot behavior [5]. For this reason, even if cognitive ergonomics is a very novel and often underestimated theme in the field of industrial HRC, it is necessary to include these aspects into the design stages of collaborative workcells.

Therefore, the aim of this paper is to investigate the current state of the art of safety as well as ergonomics (or human factors) in collaborative robotics and to identify those research fields which are of a

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https://doi.org/10.1016/j.rcim.2020.101998
Received 12 July 2019; Received in revised form 20 April 2020; Accepted 4 May 2020

high importance to bring collaborative robotics from the laboratory in the shop floor. Based on consolidated and well discussed themes in research, this work should identify where scientists should concentrate and focus in the near future to successfully implement collaborative workcells in industrial companies. Thus, this paper seeks to answer the following research questions:

RQ1: Which are the main research themes that researchers addressed in the recent scientific literature regarding safety and ergonomics (or human factors) for collaborative robotics in industry?
RQ2: What are the most emerging research challenges and research fields in safe and ergonomic collaborative robotics in industry?

After an introduction of the theoretical background in Section 1, Section 2 is describing the methodology used in this work based on a systematic literature review (SLR) methodology to identify relevant papers for this study. In Section 3 these papers are analyzed identifying sub-cluster of research fields. Section 4 is dedicated to discuss the findings from the content analysis and to provide an overview of emerging research fields and challenges for collaborative robotics in the context of safety and ergonomics (or human factors). Further in this section practical implications and limitations of this study are discussed. Section 5 summarizes the findings of this work and gives a brief outlook.

According to main results, about two third (64.2%) of analyzed papers are related to safety and about one third (35.8%) of papers are related to ergonomics (or human factors). This means that in the recent period (2015-2018) researchers invested more effort in the development of the safety aspects instead to the study of the ergonomic conditions of HRI. Nevertheless, physical and cognitive ergonomics is growing significantly in the last two years. This condition underlines the necessity to focus future works in the alignment of safety and ergonomics (or human factors) research effort. According to the results and referring to safety works, there is a higher interest in prevention (which studies safety measures that aim to operate before potential human–robot contacts occur) instead in protection (which studies safety measures that aim to minimize the effects of human–robot contacts after the physical interaction occur).

2. Materials and methods

We applied SLR in this study because it is based on a systematic, method-driven and replicable approach [6]. SLR aims to search, appraise, synthetize and analyze all the studies relevant for a specific field of research [7]. According to [8], SLR is characterized by a scientific and transparent process that aims to minimize bias through exhaustive literature searches and by providing an audit trail of the reviewer's procedures.

There are several studies on how to conduct a SLR (e.g. [7,9–10]). In our research, we applied the SLR approach as suggested by [10]. Based on this reference, we defined the following four consecutive steps for our study:

- Step 1: Establishing the research objectives of the SLR;
- Step 2: Defining the conceptual boundaries of the research;
- Step 3: Setting out the data collection by defining the inclusion/exclusion criteria;
- Step 4: Reporting the validation procedure and efforts.

2.1. Research objectives of the SLR

The objectives of this research were deduced from the research questions described in the introduction. In the SLR, we want to identify the main research themes that researchers addressed in recent scientific literature regarding safety and ergonomics (or human factors) for collaborative robotics for industrial use. The following content analysis in this SLR will help us to understand and investigate what are the most emerging research challenges and research fields in safe and ergonomic collaborative robotics. In particular, we want to understand how the results in research generated in the last years can be categorized, and where we have to concentrate in the future to successfully implement shared and collaborative workplaces in industry.

2.2. Conceptual boundaries

This research aims to analyze collaborative robotics. Thus, the setting of the conceptual boundaries was based on the terms 'collaborative robotics' and its derivations combined with terms describing its application in an industrial environment (e.g. 'industrial', 'production', 'manufacturing' or 'assembly') and, of course, considering the terms 'safety' and 'ergonomics' or 'human factors' (for simplicity, we will name this main theme only 'ergonomics' in the rest of the article).

2.3. Inclusion and exclusion criteria

In addition to the conceptual boundaries, several search criteria, in terms of database, search terms and publication period need to be defined. We used Scopus as electronic database for the keyword search, which we identified as being the most relevant for publications in the engineering and manufacturing area. A previous check of other sources such as ISI Web of Knowledge, Science Direct and Emerald did not show any major changes in relation to adding to the sources. Therefore, we decided to conduct the SLR with the Scopus database as it represents the most relevant source for our purpose.

Fig. 1 shows the applied search approach and the inclusion and exclusion criteria in relation to the search query. In different steps we identified relevant papers for our study. In a first step we identified the literature of the collaborative robotics field using the following search terms for searching in title, abstract and keywords: 'collaborative robotics', 'collaborative robot', 'cobots', 'human robot', 'human – robot' and 'human–robot'. In this first step all kind of subject areas and documents were included and only works in English language were selected. As we are interested to better understand the current state of the art and emerging research fields, we selected the last four full years as time span for this research (2015-2018). According to Scopus data, the annual paper production related to this research is starting to grow significantly from 2015, which is the starting year of the analyzed period. As a result, we obtained 7589 papers.

In a second step we concentrated on collaborative robotics in the industrial sector as robotic solutions e.g. in service industry or medicine are not in the scope of our study. Therefore, in this second step the following search terms were added through a Boolean "AND" function: 'industry', 'industrial', 'manufacturing', 'assembly' and 'production'. Through this filter in the second step we obtained 1372 relevant papers. To be sure, that important search terms were not taken into account we built a ranking of key words (Scopus keywords and author keywords) used by the identified works. The ranking list created in this way did not lead to the fact that further keywords had to be added to the search term.

In a third step we wanted to concentrate our study on relevant research works in engineering or computer science. Therefore, the search was limited to 'Journal' as source type and 'Article', 'Review' and 'Article in Press' as document type to consider only high quality literature. To focus the study on areas related to the design of collaborative workplaces we further limited the search to the subject areas 'Engineering' and 'Computer Science'. As a result we obtained 363 relevant papers as basis for our study. We want to mention that there may be also industry-related publications where ergonomics is the core topic and that are published in non-technical journals. Therefore, some relevant works may not be considered focusing on the abovementioned subject areas.

In a fourth step we divided the search results in two groups, one

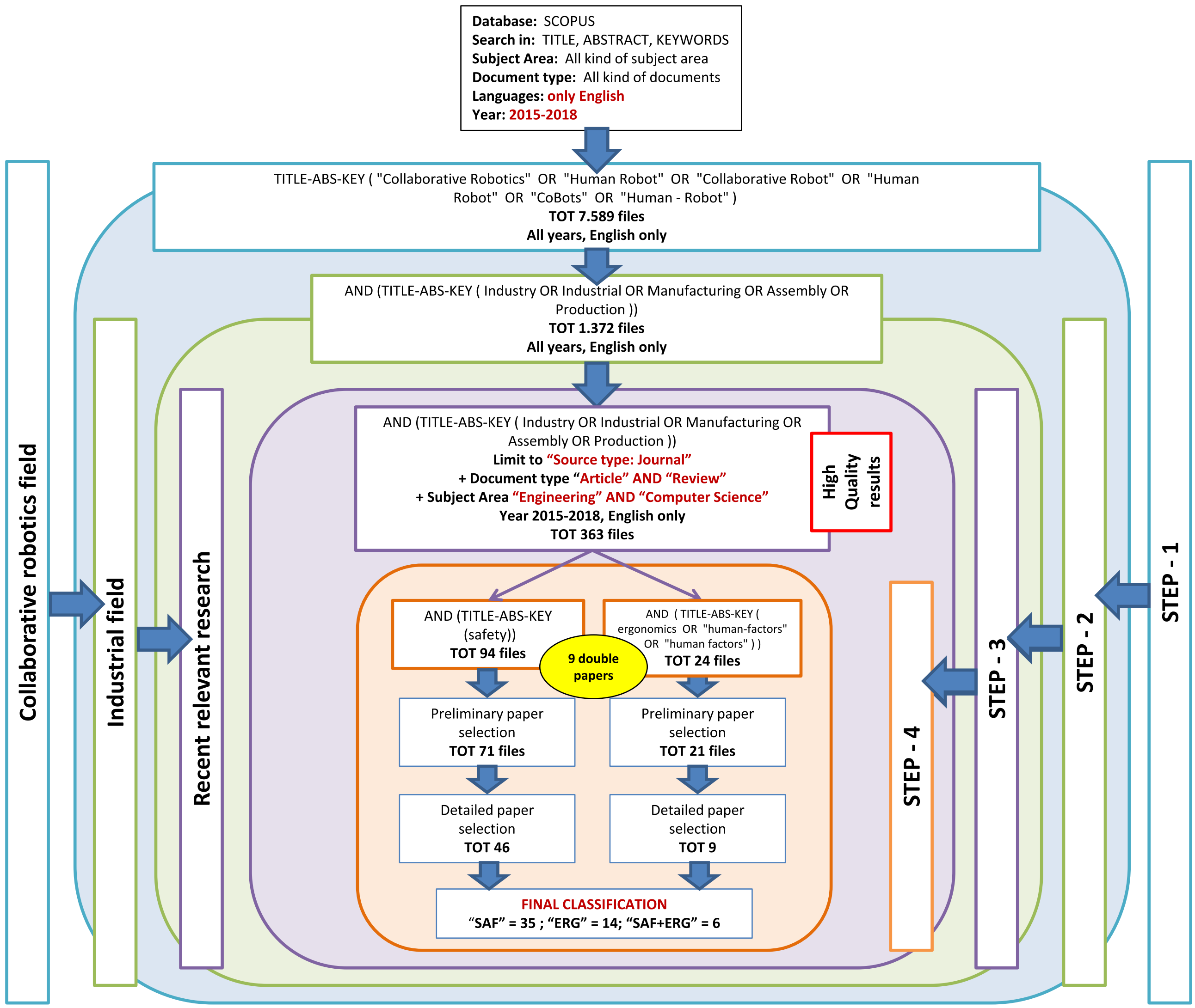


Fig. 1. Search approach and inclusion/exclusion criteria.

group for works talking about safety and the other group about ergonomics. Therefore, the abovementioned 363 works were further combined with a Boolean "AND" function with the following search terms: one group using the term 'safety' and a second group using the terms 'ergonomics', 'human factors' and 'human-factors'. 94 of the 363 papers are related to the first group while 24 of the 363 papers are related to the second group. A total of 9 papers is relevant to safety and to ergonomics as well; therefore these 9 papers are counted in both groups. The following procedure of validation of the search results to obtain a final list of relevant papers for our study is described in the next Section 3.4.

2.4. Validation of the search results

The appropriateness of the identified literature references to the aims of the study is crucial for every SLR. Often, the search results treat the subject of the SLR study as only incidental or superficial. To ensure the appropriateness of the search results, we applied a relatively straightforward coding scheme which evaluated the appropriateness of a search result using a score of 1–2 (where 2 denotes high appropriateness and 1 denotes low appropriateness). The screening was carried out in two phases by three independent researchers. In the first phase, (1° round of screening) only the title and abstract were read. In the second phase (2° round of screening), the whole paper was examined. We calculated an inter-rater reliability for each paper by evaluating the difference in scoring. Where the three independent raters came to the same conclusion, i.e., zero differences or the highest inter-rater reliability, the papers were directly included into the analysis. Papers where differences in the coding occurred were discussed in order to result in 100% agreement between the three researchers.

In the first round of screening, by reading the paper title and abstract, the number of papers related to safety reduced from 94 files to 71 files while for those related to ergonomics the papers reduced from 24 to 21.

In the second round of screening, by reading the whole paper, the number of papers related to safety reduced from 81 to 46 files. The number of papers related to ergonomics reduced from 21 to 9 papers. According to papers content, an amount of 8 papers were moved from safety to ergonomics, 1 paper was moved from ergonomics to safety, 4 papers were moved from safety to safety and ergonomics and 2 papers were moved from ergonomics to safety and ergonomics. Appendix provides details of paper encoding and final classification.

In total, we analyzed 118 papers (94 in safety plus 24 in ergonomics minus 9 works in both categories) of which 63 were scrapped due to the screening as described above. The following considerations and analysis are based on the finally obtained database of papers relevant for our study: total of 55 papers, 35 relevant only for safety, 14 relevant only for ergonomics and 6 relevant for both safety and ergonomics.

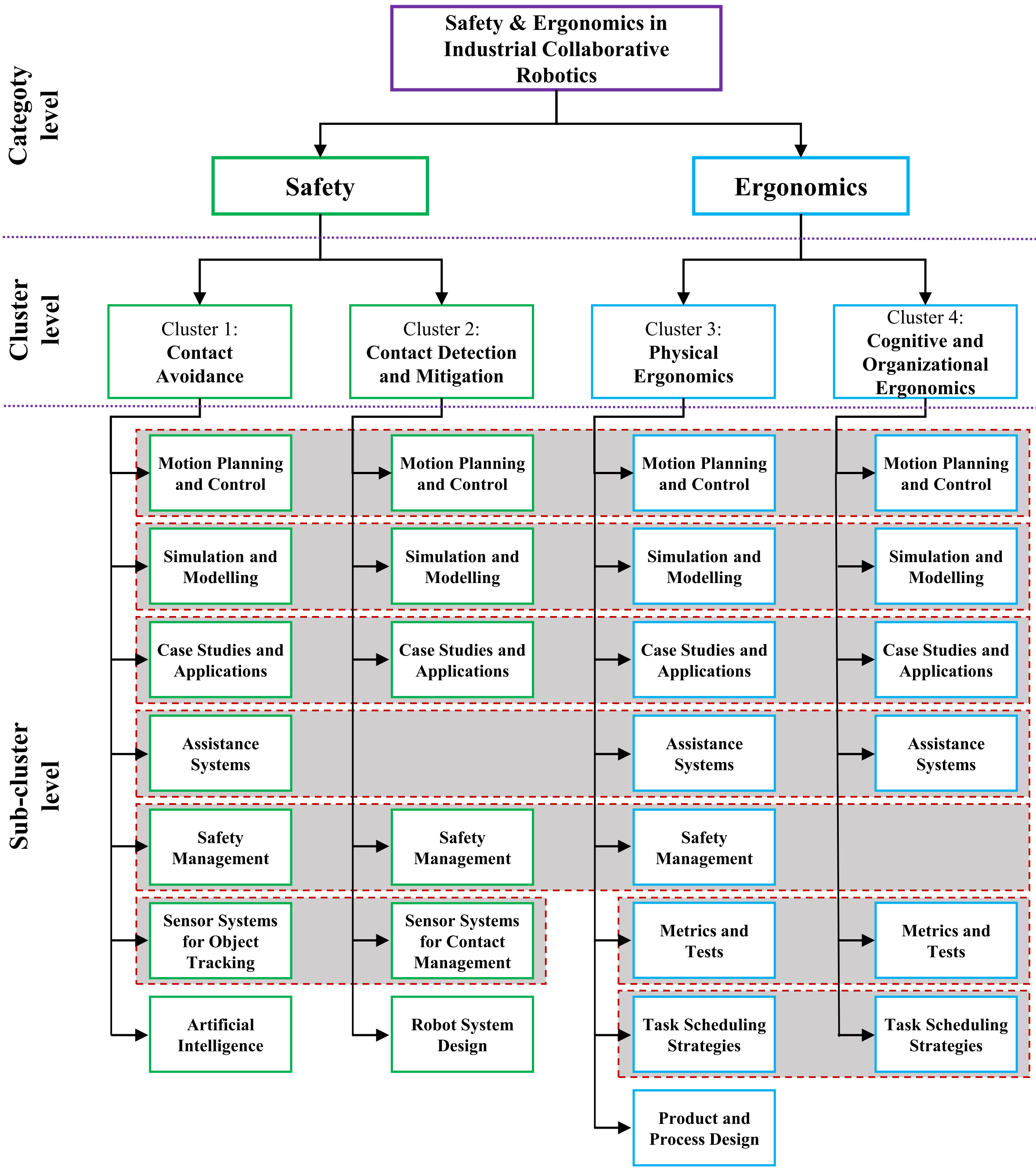


Fig. 2. Identification of categories, clusters and sub-clusters.

3. Content analysis of identified scientific literature on safety and ergonomics in industrial collaborative robotics

The following analysis is based on a primary content division in ‘safety’ and ‘ergonomics’. For each main theme, a further cluster and related sub-cluster division is provided. This classification was adopted after carefully reading all identified works and categorizing all works. The identified clusters represent macro-categories, which summarize the top-level concepts discussed in the research papers. Sub-clusters identify successive partitions of a cluster and are used to specify more detailed subjects of the scientific literature. They also help to identify research themes that are of interest to all, only to some or only to a single cluster. The proposed categorization in clusters and sub-clusters as well as the relationship of a sub-cluster with a cluster is illustrated in Fig. 2.

‘Contact Avoidance’ as well as ‘Contact Detection and Mitigation’ were identified as cluster 1 and 2 in the category regarding works on safety. For the works regarding ergonomics, ‘Physical Ergonomics’ as well as ‘Cognitive and Organizational Ergonomics’ have been defined as cluster 3 and 4. The following lower-level categorization into sub-cluster shows three main arguments, which could be assigned to all four identified clusters: ‘Motion Planning and Control’, ‘Simulation and Modelling’ as well the presentation of ‘Case Studies and Applications’. The use of ‘Assistance Systems’ is discussed in research about Contact Avoidance (cluster 1) as well as physical and cognitive/organizational ergonomics (clusters 3 and 4). Methods for ‘Safety Management’ in collaborative workplaces are relevant for Contact Avoidance (cluster 1), contact detection/mitigation (cluster 2) as well as Physical Ergonomics (cluster 3). The development of ‘Sensor Systems for Object Tracking’ is an important research theme to avoid or detect/mitigate contacts or

Table 1
Contact avoidance: recent research themes and contents in each sub-cluster.

References No	Authors	Year	Sub-clusters Motion Planning and Control	Simulation and Modelling	Case Studies and Applications	Assistance Systems	Safety Management	Sensor Systems for Object Tracking	Artificial Intelligence	Test location
[11]	Rajnathsing and Li	2018		Workplace digital representation	Mimic pick-and-place and assembly experiments			**Monitoring system**	**Neural Network**	not specified
[12]	Long et al.	2018	Novel time scaling method		Exemplifying co-existence experiments		**Dynamic safe zones mode transition method**	Dynamic optical scanners		IRT Jules Verne (Nantes)
[13]	Pereira and Althoff	2018	**Dynamic path planner**	**Future occupancy human dynamic model algorithm**	Publicly available motion capture test					Technisches Universitaet Muenchen
[14]	Ragaglia et al.	2018	**Sensor fusion trajectory generation algorithm**	Noise-free human kinematic configuration	Pick and place experiments		Human space occupancy prediction novel strategy	Sensor fusion data acquisition		Politecnico di Milano, Johns Hopkins University
[15]	Xia et al.	2018		Quantitative regression model	Prototypical experiments			**Wearable tri-mode capacity proximity sensor**	**SVM machine learning algorithm**	not specified
[16]	Matsas et al.	2018	**Adaptive techniques for trajectory modification**	Virtual reality simulation	Pre-impregnated carbon fabric hand lay-up process	**Real time dynamic stimuli (audio/video/alarm)**				National Technical University of Athens
[17]	Lippi and Marino	2018	**Safety index or impedance approach trajectory planning**	Multi-robot scenario simulation	Transport and picking		**Safety index**			Università di Salerno
[18]	Heydaryan et al.	2018	**Decision making method based on hierarchical task analysis**	Virtual environment software	Automotive disk brake assembly					Politecnico di Torino
[19]	Michalos et al.	2018			Automotive high-payload assembly	**Enabling technologies (manual guidance, wearable devices, AR)**	Safety analysis			University of Patras
[20]	Dannapfel et al.	2018			Automotive heavy-duty assembly		**Heavy-duty HRC concept planning framework**			Aachen University
[21]	Rengevic et al.	2017			Vision system test			**Computer vision system**		University of Zilina
[22]	Brending et al.	2017			Speed and laboratory test		**Real-time controlled network system (IT driven approach)**	Camera system based data fusion evaluation software		not specified
[23]	Meziane et al.	2017	**Collision free trajectory generating method**	Static and dynamic simulations	Flexible manufacturing system assembly				**Neural Network for waypoints generation**	University of Quebec
[24]	Spirescu et al.	2017			**Automotive industry**					not specified
[25]	Makris et al.	2017	Station controller	Task hierarchical model, Simulation Platform	Automotive dual-arm assembly		**Technology investigation (IT based approach)**	3D sensing devices		automotive laboratory machine shop
[26]	Kimmel and Hirche	2017	**Dynamic constraint invariance control scheme**		Human hand collision avoidance experiments					not specified
[27]	Bdiwi et al.	2017			Automotive heavy-duty assembly		**Safety function based strategy**	**System for workspace monitoring**		not specified
[28]	Savazzi et al.	2016		**Models for the radio propagation effects capture, Operator**	Industrial plant experiments			**Free-localization wireless device**		not specified

(*continued on next page*)

Table 1 (*continued*)

References No	Authors	Year	Sub-clusters Motion Planning and Control	Simulation and Modelling	Case Studies and Applications	Assistance Systems	Safety Management	Sensor Systems for Object Tracking	Artificial Intelligence	Test location
				localization accuracy prediction simulation						
[29]	Zhang et al.	2016	**Calculation-based path planning**		System efficacy evaluation experiments		Safety and efficiency performance method comparison	Kinect vision system		not specified
[30]	Rengevic and Kumicakova	2016		**ROS based primitive task simulation, Method planner simulation**	Probabilistic roadmap experiments			Monitoring system		not specified
[31]	Shackleford et al.	2016			Performance evaluation scenario		**Sensor performance validation methodology**	Human detection and tracking algorithm and system		not specified
[32]	Zanchettin et al.	2016	**Joint space kinematic control strategy**		Dual arm robot manipulation experiments		**Human–robot relative distance metrics**			Politecnico di Milano
[33]	Cherubini et al.	2016	**Trajectory generation, admittance control, Safety monitoring integrated framework**		Homikinetic joint assembly			**Visual gesture monitoring system**		PSA (Peugeot Citroën) line
[34]	Wang	2015	**Web based monitoring and control system**	Data and depth images model	Exemplifying assembly experiments			**Sensor driven model based approach**		not specified
[35]	Chen et al.	2015			Grasping and handling experiments	**Supportive glove for position and orientation data**		**RGB-D camera system for gesture recognition**		Tsinghua University
[36]	Ibarguren et al.	2015			Algorithm performances estimation disassembly experiment			**Laser rangefinders security framework, Multiple target tracking algorithm**		not specified
[37]	Ceriani et al.	2015	**Safe and task-consistent control system**		Free-move and pick experiments		**Safety-based classification of task constraints**	Distributed distance sensor		not specified

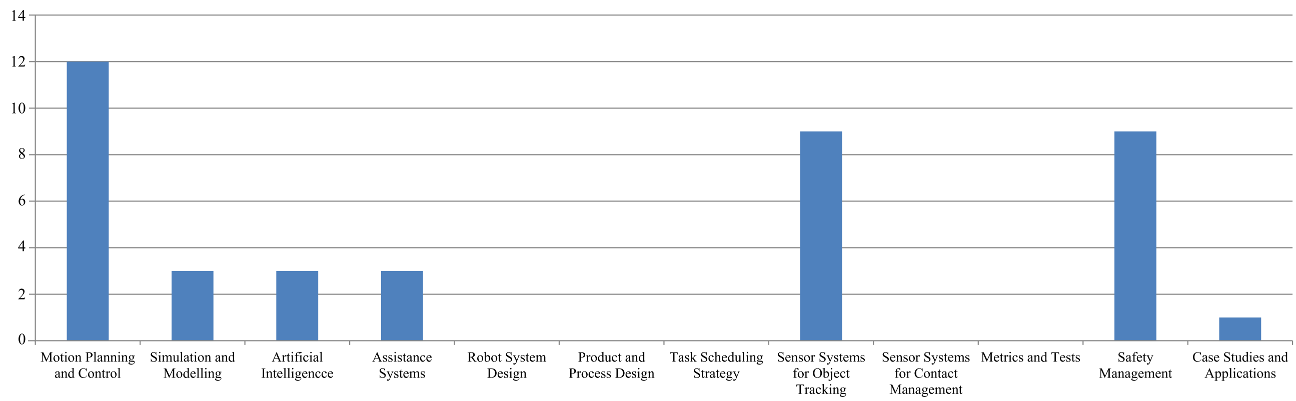


Fig. 3. No of papers related to the main research themes for Contact Avoidance.

collisions between the robot and humans or other objects (cluster 1 and 2). A current interest in research seems to exist regarding the validation of physical and cognitive ergonomics with recent research on 'Metrics and Tests'. Further Contact Avoidance (cluster 1) can be realized or supported by using new algorithms from 'Artificial Intelligence'. To improve the detection and especially the mitigation of collisions (cluster 2) current research is carried out in 'Robot System Design'. For Physical Ergonomics (cluster 3) current research is conducted for developing new 'Task Scheduling Strategies' and for advanced 'Product and Process Design'. Further, in cluster 4 on cognitive/organizational ergonomics the cognitive aspects of 'Task Scheduling Strategies' have also been addressed in several works.

In the following subsections we report and summarize the main findings in the content analysis to argument the proposed categorization in Fig. 2 and to give the reader an overview of recent research activities and results in the shown clusters and sub-clusters.

3.1. Safety – Cluster 1: contact avoidance

The concept of Contact Avoidance is to ensure operators safety (in terms of mechanical risk) by pre-empting dangerous contacts using preventive methodologies and systems.

Sub-cluster 'Motion Planning and Control':

Pereira and Althoff [13] developed a computing volumes method for occupancy prediction based on a dynamic path planner. Ragaglia et al. [14] presented an algorithm for the prediction of human space occupancy. Matsas et al. [16] proposed adaptive techniques for trajectory modification. Lippi and Marino [17] developed a trajectory modification strategy based on impedance. Heydaryan et al. [18] presented a decision making method based on hierarchical task analysis. Meziane et al. [23] proposed a dynamic obstacle avoidance supported by a neural network. Kimmel and Hirche [26] developed an invariance control scheme for HRI. Zhang et al. [29] presented a safety methodology based on interval Kalmann Filter technique. Zanchettin et al. [32] proposed a control strategy based on metrics for safety evaluation. Cherubini et al. [33] developed a safety framework based on visual gesture monitoring. Wang [34] presented a web-based remote control system for motion control. Ceriani et al. [37] proposed a task-consistent avoidance based on a constraint classification strategy.

Sub-cluster 'Simulation and Modelling':

Savazzi et al. [28] developed a simulation toolset for the wireless detection and localization of humans. Rengevic and Kumicakova [30] presented a simulation of basic robot tasks by using ROS Software.

Sub-cluster 'Case Studies and Applications':

Spirescu et al. [24] developed a system which is reproducing safe working conditions and implemented it in an industrial case at Dacia Renault company.

Sub-cluster 'Assistance Systems': Matsas et al. [16] developed an audio/visual cognitive aid system based on the use of Virtual Reality. Michalos et al. [19] presented Augmented Reality technologies and wearable devices for HRI safety improvements. Chen et al. [35] presented glove sensors and a RGB-D camera systems for gesture recognition.

Sub-cluster 'Safety Management':

Long et al. [12] developed a mode transition methodology supported by laser scanner and based on a time-scaling method. Lippi and Marino [17] presented a trajectory modification strategy based on safety index. Dannapfel et al. [20] proposed an approach for concept planning of heavy-duty HRI. Brending et al. [22] developed an Information Technology (IT) driven approach for collaborative workplaces. Makris et al. [25] presented an IT approach for the simplification of cell structure and program. Bdiwi et al. [27] proposed a safety function strategy based on new HRI taxonomy, also including collision avoidance levels. Shackleford et al. [31] developed a test procedure for sensors metrics validation. Zanchettin et al. [32] presented a metrics for safety evaluation and related control strategy. Ceriani et al. [37] proposed a constraint classification strategy for task-consistent collision avoidance.

Sub-cluster 'Sensor Systems for Object Tracking':

Rajnathsing and Li [11] developed a monitoring system by implementing a neural network. Xia et al. [15] proposed a multi-functional sensor based on a machine learning algorithm. Rengevic et al. [21] presented a computer vision system design for object recognition. Bdiwi et al. [27] developed a safety function strategy algorithm for monitoring the entire workspace. Savazzi et al. [28] proposed a wireless system for human detection and localization by using a simulation toolset. Cherubini et al. [33] presented visual gesture monitoring for a safety monitoring framework. Wang [34] developed a web-based remote monitoring system. Chen et al. [35] proposed a gesture recognition system based on RGB-D camera and glove sensors. Ibarguren et al. [36] presented a security framework based on multiple target tracking algorithm.

Sub-cluster 'Artificial Intelligence':

Rajnathsing and Li [11] used neural networks to develop a monitoring system. Xia et al. [15] proposed a machine learning algorithm for the development of a multi-functional sensor. Meziane et al. [23] proposed a neural network for dynamic obstacle avoidance.

Table 1 summarizes the most important research themes and contents investigated in recent years in the individual sub-cluster of cluster 1 for Contact Avoidance. The words which are highlighted in bold are the main topics of the related papers (maximum two per paper). The others represent additional contents included in the research.

Summary:

According to the data (see Table 1 and Fig. 3), the most developed research themes for Contact Avoidance are Motion Planning and Control, Sensor Systems for Object Tracking and Safety Management. Minor contributions come from Simulation and Modelling, Artificial Intelligence, Assistance Systems and case studies and applications. For

Table 2
Contact detection and mitigation: recent research themes in each sub-cluster.

Reference No	Authors	Year	Sub-clusters: Motion Planning and Control	Simulation and Modelling	Case Studies and Applications	Sensor Systems for Contact Management	Safety Management	Robot System Design	Test location
[38]	Ren et al.	2018	**Extended State Observer closed-loop control**	Quantitative comparison simulation	Human impact experiments	**Proprioceptive internal sensor collision detection system**			not specified
[39]	Pang et al.	2018			Contact collision force experiments	**Piezoresistive 3D flexible robot skin**	**Safety strategy for natural HRI**		not specified
[40]	Roveda et al.	2018	**Two layers discrete impedance and admittance control algorithm**	Impact modelling	Probing task experiments				Consiglio Nazionale delle Ricerche
[41]	Merckaert et al.	2018			Measurement arm deflection experiments			**Additional measurement arm error compensation method**	not specified
[42]	Dean-Leon et al.	2018	**Multimodal control framework**		Fruit picking experimental validation	**Auto-calibrated and self-configurable multi-modal robot skin**			Technisches Universitaet Muenchen
[65]	Vemula et al.	2018		**Spring-damper human body model**	Collision impact experiments		Power flux metric for application design	**Power flux safety metric for manipulator design**	not specified
[43]	Li et al.	2017	**Impedance control**	Compliant joint and motor model	Dual-arm humanoid robot and massage robot experiments			**Serial integrated rotary joint**	not specified
[44]	Labrecque et al.	2017	**Control strategy**		Part insertion and automotive deck lid assembly			**Macro-mini under-actuated manipulator architecture**	not specified
[27]	Bdiwi et al.	2017			Automotive heavy-duty assembly		**Safety function strategy, HRI levels classification**		not specified
[45]	Labrecque et al.	2016			Performance assessment test			**Macro-micro manipulator architecture**	not specified
[46]	Lee and Song	2016		**Collision detection friction-based model**	Human collision experiment	**Sensor-less collision system**			Korea University
[47]	Dagalakis et al.	2016			Biosimulant materials artifacts test	**Dynamic impact testing and calibration instrument**			National Institute of Standards and Technology (USA)
[33]	Cherubini et al.	2016	**Trajectory generation, admittance control, Safety monitoring integrated framework**		Homikinetic joint assembly				PSA (Peugeot Citroën) line
[48]	Scholer et al.	2015		Processing algorithm	**Automotive water leak test**				ZeMA Center for Mechatronics and Automation
[49]	Marvel et al.	2015			Exemplifying parts assembly and surface finishing		**Task based risk assessments method**		not specified
[50]	Marcan et al.	2015			Pick and place programming			**ROS based application development**	not specified

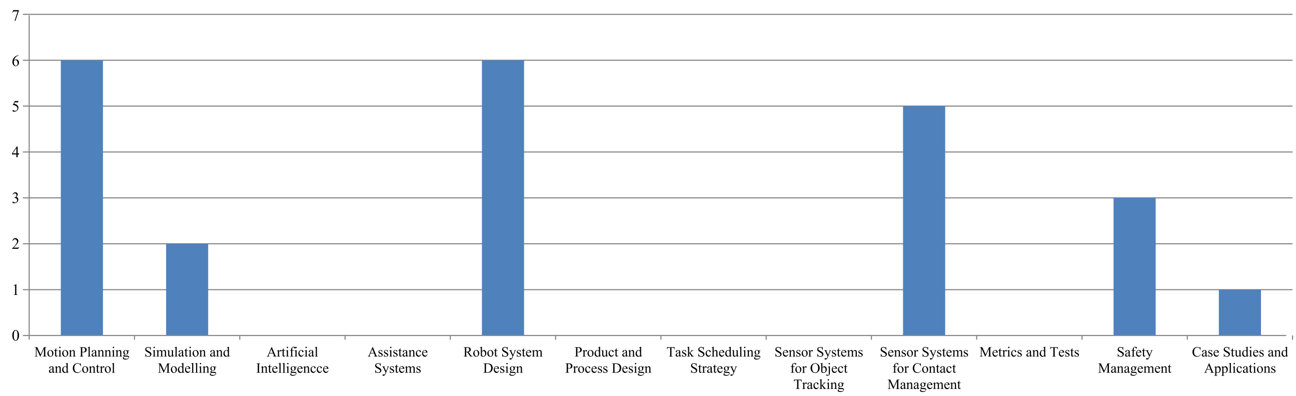


Fig. 4. No of papers related to the main research themes for Contact Detection and Mitigation.

Motion Planning and Control main contents refer to human-motion prediction, trajectory modification and motion control strategies. For Sensor Systems for Object Tracking main contents refer to the development and integration of monitoring and computer vision systems for human localization, workspace control and gesture recognition. For Safety Management, main topics refer to the development of procedure and methodologies, metrics and indexes for contacts prevention management.

3.2. Safety – Cluster 2: contact detection and mitigation

The concept of Contact Detection and Mitigation is to ensure operators safety (in terms of mechanical risk) through the reduction of the collision energy which can be exchanged during unwonted or unexpected human–robot contacts.

Sub-cluster 'Motion Planning and Control':

Cherubini et al. [33] developed an active and passive robot behavior system based on intrinsic collision detection. Ren et al. [38] proposed an algorithm for whole-body collision detection by using an extended state observer method. Roveda et al. [40] presented a two layers discrete impedance and admittance control algorithm. Dean-Leon et al. [42] developed a multimodal control framework for an artificial robot skin. Li et al. [43] proposed a passive and active compliance controller for a serial integrated rotary joint. Labrecque et al. [44] presented a control for a macro–mini under-actuated manipulator.

Sub-cluster 'Simulation and Modelling':

Vemula et al. [65] presented a linear spring-damper model for the representation of the physical impact between the robot and the human body region. Lee and Song [46] developed a joint friction and motor current model for a sensorless detection method.

Sub-cluster 'Case Studies and Applications':

Scholer et al. [48] developed a new application for HRC in the continuous assembly line.

Sub-cluster 'Safety Management':

Bdiwi et al. [27] developed a safety function strategy based on new HRI taxonomy, also including a direct physical interaction level. Pang et al. [39] proposed a safety strategy based on a 3D flexible robot skin. Marvel et al. [49] presented a task-based methodology for the description of HRC safety.

Sub-cluster 'Sensor Systems for Contact Management':

Ren et al. [38] developed a collision detection method by using a proprioceptive sensors system. Pang et al. [39] proposed a 3D flexible robot skin. Dean-Leon et al. [42] presented an artificial robot skin supported by a multimodal control framework. Lee and Song [46] presented a sensorless detection method based on joint friction and motor current model. Dagalakis et al. [47] developed a dynamic impact testing and calibration instrument.

Sub-cluster 'Robot System Design':

Merckaert et al. [41] developed an error compensation method for robot design. Li et al. [43] proposed a serial integrated rotary joint controlled by passive and active compliance. Labrecque et al. [44] presented a macro–mini underactuated manipulator architecture and control. Further, Labrecque et al. [45] developed a low impedance and high bandwidth mini mechanism. Marcan et al. [50] presented a ROS based approach for robotic workstation design. Vemula et al. [65] presented a novel design metric based on maximum power flux density for the assessment of the severity of a transient physical contact.

Table 2 summarizes the most important research themes and contents investigated in recent years in the individual sub-cluster of cluster 2 for Contact Detection and Mitigation. The words which are highlighted in bold are the main topics of the related paper (maximum two per paper). The others represent additional content included into the research work.

Summary:

According to the data (see Table 2 and Fig. 4), the most developed research themes for Contact Detection and Mitigation are Motion Planning and Control, Robot System Design and sensor systems for contact management. Minor contributions come from Simulation and Modelling, Safety Management and case studies and applications. For Motion Planning and Control main contents refer to control strategies. For Robot System Design main contents refer to the development of robot hardware and design methodology. For sensor systems for contact management main contents refer to the development of sensor devices and detection methodologies.

3.3. Ergonomics – Cluster 3: physical ergonomics

Physical Ergonomics in industrial HRI deals with the principles of reduction of activities biomechanical workload by using collaborative robots as advanced tools for the improvement of operators physical wellbeing.

Sub-cluster 'Motion Planning and Control':

Heydaryan et al. [18] developed a control framework for trajectory definition, also considering Physical Ergonomics factors. Sadrfaridpour and Wang [54] proposed a motion control framework for the integration of HRI factors. Faber et al. [55] presented a cognitive control unit for Physical Ergonomics conditions assessment.

Sub-cluster 'Case Studies and Applications':

Cherubini et al. [33] developed a state of the art collaborative cell for the improvement of operators Physical Ergonomics.

Sub-cluster 'Assistance Systems':

Michalos et al. [19] developed the use of enabling technologies for a multimodal interaction system. Tang and Webb [53] proposed a hand gesture control system designed for the improvement of Physical Ergonomics conditions.

Sub-cluster 'Safety Management':

Sadrfaridpour and Wang [54] developed a motion control framework for the integration of HRI factors.

Table 3
Physical ergonomics: recent research themes in each sub-cluster.

References No	Authors	Year	Sub-clusters MotionPlanning andControl	Simulation andModelling	Case Studies andApplications	Assistance Systems	SafetyManagement	Metrics and Tests	TaskScheduling Strategy	Product and ProcessDesign	Test location
[51]	Michalos et al.	2018			Automotive rear axle assembly			NIOSH based Ergonomics criteria	**System variables-based tasks assignment**	CAD model data algorithm	automotive assembly station
[52]	Pearce et al.	2018			Various real-world factory tasks			Strain and makespan indexes	**Framework for task assignments generation**		Institute of Technology (workshop)
[53]	Tang and Webb	2018	Gesture control system for motion control and programming		Gesture control and teach pedant ergonomic experiments	**Hand gesture robot control system**		RULA index, Exploratory ergonomic study		**Teach pedant design for the reduction of musculoskeletal injury**	not specified
[54]	Sadrfaridpour and Wang	2018	**Optimal robot motion control**		Automotive center-console parts assembly		**Framework for physical factors integration**	Path selection metrics		Physical workload reduction	not specifierd
[18]	Heydaryan et al.	2018	**Control framework for trajectory definition**	Virtual reality simulation	Automotive disk brake assembly			Qualitative process efficiency evaluation	**Hierarchical task analysis**	Physical workload reduction	not specifierd
[19]	Michalos et al.	2018			Automotive high-payload assembly	**Manual guidance and wearable sensor enabling technologies**	Multimodal interaction system	MURI analysis	**Capability based task assessment**	Physical workload reduction	not specifierd
[20]	Dannapfel et al.	2018			Automotive heavy-duty assembly			Ergonomic Assessment Worksheet KPI	**Heavy-duty HRC planning method**		Automotive company
[66]	Maurice et al.	2018	Non-biological and biological robot trajectory		Non-biological and biological velocity patterns experiments			**Humans adjustment to non-biological robot motion pattern**			Northeastern University
[55]	Faber et al.	2017	**Cognitive unit control system**	Ergonomics process assessment model	Stromberg carburetor assembly				**Human-like graph-based assembly sequence**		not specified
[25]	Makris et al.	2017	Hierarchical programming, Automatic robot motion generation	Task hierarchical model	Automotive dual-arm assembly	Gesture and voice commands system		OWAS, SSP, Fatigue, LBA, RULA indexes simulation	**Task hierarchical sequencing**		Automotive company
[33]	Cherubini et al.	2016	Trajectory generation, admittance control, Safety monitoring integrated framework		**Homikinetic joint assembly**	Visual gesture monitoring				Physical workload reduction	PSA (Peugeot Citroën) line

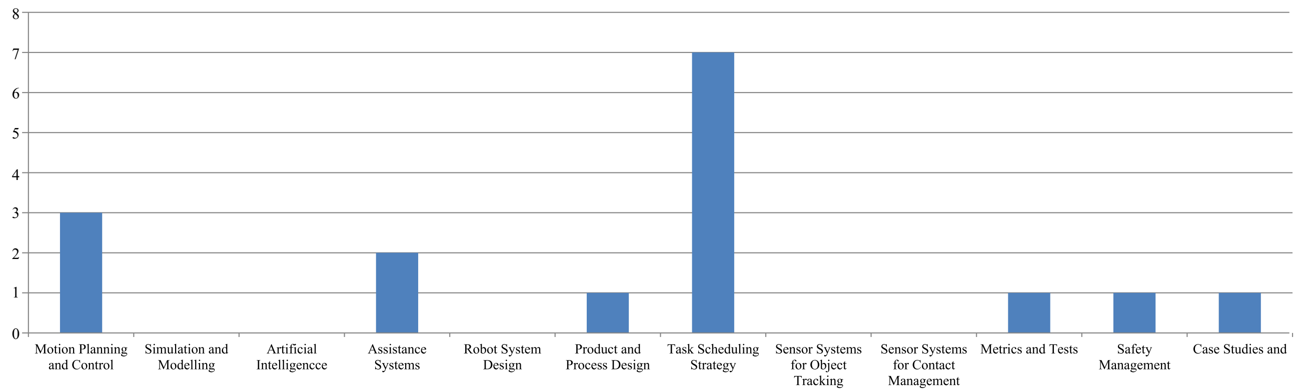


Fig. 5. No of papers related to the main research themes for Physical Ergonomics.

Sub-cluster 'Metrics and Tests':

Maurice et al. [66] presented an assessment about the human ability to adapt to non-biological movements when physically interacting with a robot.

Sub-cluster 'Product and Process Design':

Tang and Webb [53] developed a teach pendant design for the reduction of musculoskeletal injury.

Sub-cluster 'Task Scheduling Strategies':

Heydaryan et al. [18] developed a control framework based on a decision-making method for HRC, also considering Physical Ergonomics factors. Michalos et al. [19] proposed a multimodal interaction system based on enabling technologies. Dannapfel et al. [20] presented a heavy-duty HRC planning framework, also considering Physical Ergonomics factors. Makris et al. [25] developed a hierarchical model-based flexible assembly cell which also aims to improve Physical Ergonomics. Michalos et al. [51] proposed a CAD-based multi-criteria method for human–robot assembly task sharing, also considering Physical Ergonomics factors. Pearce et al. [52] presented a strain index-based optimization framework for human–robot task assignments and schedule. Faber et al. [55] developed a graph-based assembly sequence planner for the improvement of Physical Ergonomics conditions.

Table 3 summarizes the most important research themes and contents investigated in recent years in the individual sub-cluster of cluster 3 for Physical Ergonomics. The words which are highlighted in bold are the main topics of the related paper (maximum two per paper). The others represent additional content included into the research work.

Summary:

According to the data (see Table 3 and Fig. 5), the most developed research theme for Physical Ergonomics is Task Scheduling Strategy. Minor contributions come from Motion Planning and Control and Assistance Systems. For Task Scheduling Strategy, the main contents refer to human–robot task sequence assignment and planning by integrating Physical Ergonomics aspects.

3.4. *Ergonomics – Cluster 4: cognitive and organizational ergonomics*

Cognitive ergonomics in industrial HRI deals with the principles of interaction acceptability by minimizing mental stress and psychological discomfort which could be provided to operators while sharing the workspace with robots. On the other hand, organizational ergonomics refers to the optimization of social technical systems in terms of organizational structures, policies and processes.

Sub-cluster 'Motion Planning and Control':

Long et al. [12] developed a control architecture for a better system acceptability. Sadrfaridpour and Wang [54] proposed a framework for finding the optimal velocity of the robot. Faber et al. [55] studied a cognitive control unit for the improvement of cognitive ergonomics conditions. Medina et al. [63] developed a risk-sensitive control scheme for anticipatory haptic assistance for human effort minimization.

Sub-cluster 'Simulation and Modelling':

Matsas et al. [16] developed a virtual environment simulation for the user acceptability evaluation by using cognitive audio-visual supports. Matsas and Vosniakos [58] presented a virtual reality simulation-based training system for HRC acceptability test. Koppenborg et al. [59] proposed a virtual reality based speed and path predictability test. Hugues et al. [62] developed a virtual reality simulation for testing the human-like robot movements' acceptability.

Sub-cluster 'Assistance Systems':

Matsas et al. [16] developed cognitive audio-visual supports for user acceptability evaluation in a virtual environment. Wang et al. [56] proposed a natural language teaching-learning-collaboration model as potential aid system.

Sub-cluster 'Metrics and Tests':

Matsas and Vosniakos [58] developed a HRC acceptability test by using a virtual environment. Koppenborg et al. [59] presented a test for the speed and path predictability by using virtual reality. Maurtua et al. [60] proposed a test for workers-trust in safety measurement and the validation of different HRI alternatives. Charalambous et al. [61] developed a human factors readiness level for HRC. Hugues et al. [62] presented an acceptability test for human-like robot movements' acceptability by using virtual reality. Charalambous et al. [67] presented an organizational framework related to human factors to be considered for a successful implementation of HRC.

Sub-cluster 'Task Scheduling Strategies':

Faber et al. [55] developed a graph-based assembly sequence planner for the improvement of cognitive ergonomics conditions. Wang et al. [56] presented a teaching-learning-collaboration model by using a natural language methodology. Rahman and Wang [57] proposed an optimization strategy for trust-based subtask allocation.

Table 4 summarizes the most important research themes and contents investigated in recent years in the individual sub-cluster of cluster 4 for Cognitive and Organizational Ergonomics. The words which are highlighted in bold are the main topics of the related paper (maximum two per paper). The others represent additional content included into the research work.

Summary:

According to the data (see Table 4 and Fig. 6), the most developed research theme for Cognitive and Organizational Ergonomics are Metrics and Tests, Motion Planning and Control and Simulation and Modelling. Minor contributions come from Assistance Systems and Task Scheduling Strategy. For Metrics and Tests main contents refer to the development of evaluation methodology for robot acceptability and organizational framework for successful HRI applications implementation. For Motion Planning and Control main contents refer to control strategies related to cognitive aspects of HRI. For Simulation and Modelling main contents refer to the development of virtual reality experiences for the evaluation of the cognitive aspects of HRI.

Table 4
Cognitive and organizational ergonomics: recent research themes in each sub-cluster.

Reference No	Authors	Year	Sub-clusters Motion Planning and Control	Simulation and Modelling	Case Studies and Applications	Assistance System	Metrics and Tests	Task Scheduling Strategy	Test location
[56]	Wang et al.	2018		Teaching-learning collaboration model		**Teaching-learning-collaboration**	Learning-algorithm based strategy	**Learning by demonstration action planning**	Subaward from Advanced Robotics for Manufacturing Institute
[57]	Rahman and Wang	2018			Lightweight parts (LEGO) assembly	Display method and robot-face screen	Real-time trust measurement	**Optimum subtask allocation and real-time trust based task re-allocation**	Clemson University
[12]	Long et al.	2018	**Control architecture**				Questionnaire for qualitative evaluation	H-R coesistence experimental demonstration	Industrial scenario (not specified)
[16]	Matsas et al.	2018		**Virtual reality environment and scene**		**Real time dynamic stimuli (audio / video / alarm)**	User satisfaction metrics	Pre-impregnated carbon fabric hand lay-up process	National Technical University of Athen
[54]	Sadrfaridpour and Wang	2018	**Optimal robot motion control, Trust-based robot path selection strategy**			Robot facial expression	Humans-trust based path selection	Automotive center-console parts assembly	Laboratory (not specified)
[55]	Faber et al.	2017	**Cognitive control unit**	Human metal model	Stromberg carburetor assembly			Human-like graph-based assembly sequence	not specified
[58]	Matsas and Vosniakos	2017		**Virtual reality training system**	Aerospace tape-laying composite parts handling		**HRC acceptability test**		National Technical University of Athens
[59]	Koppenborg et al.	2017		**Virtual reality simulation and case study**	Products manufacturing and quality check		**Speed and path predictability test**		Laboratory (not specified)
[60]	Maurtua et al.	2017			Fair events based on Safety measures interaction		**Workers trust test, Effectiveness and acceptance of alternative validation**		Faire experiments with volunteers from the audience
[61]	Charalambous et al.	2017			Hybrid block assembly		**Maturity readiness evaluation index**		Industrial shop floor
[62]	Hugues et al.	2016	Human-like robot movements generator	**Virtual reality environment and case study**	Car door assembly		**Impact on the human-likeness evaluation**		Industrial scenario (not specified)
[63]	Medina et al.	2015	**Risk-sensitive control scheme for anticipatory haptic assistance**	Data-driven stochastic model	Virtual maze experiment				not specified
[67]	Charalambous et al.	2015			Qualitative exploratory case study		**Roadmap of the key organisational human factors**		Aerospace manufacturing company

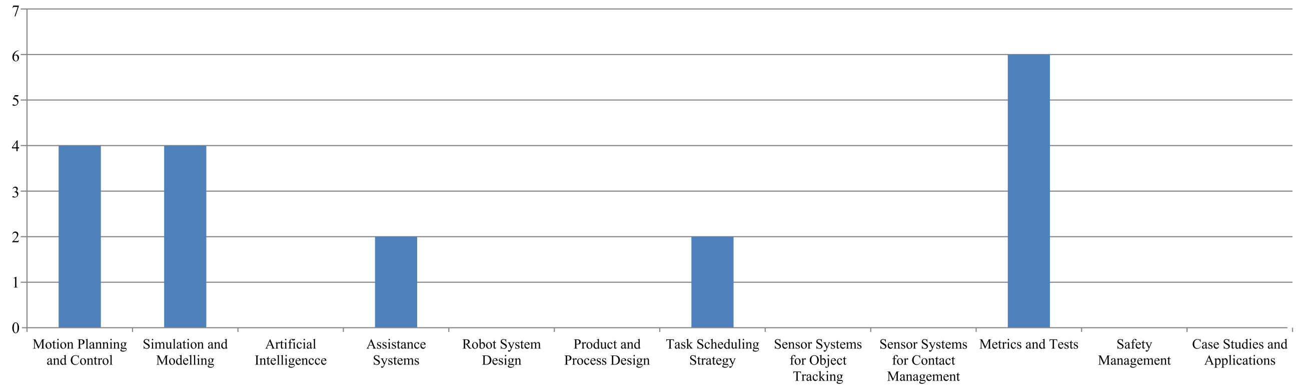


Fig. 6. No of papers related to the main research themes for Cognitive and Organizational Ergonomics.

Table 5
Relationship of papers which are related to multiple sub-clusters.

		Safety Contact Avoidance	Contact Detection and Mitigation	Ergonomics Physical Ergonomics	Cognitive and Organizational Ergonomics
Safety	**Contact Avoidance**				
	Contact Detection and Mitigation	[27,33]			
Ergonomics	**Physical Ergonomics**	[18,–20,25,33]	[33]		
	Cognitive and Organizational Ergonomics	[12,16]	(/)	[54,55]	

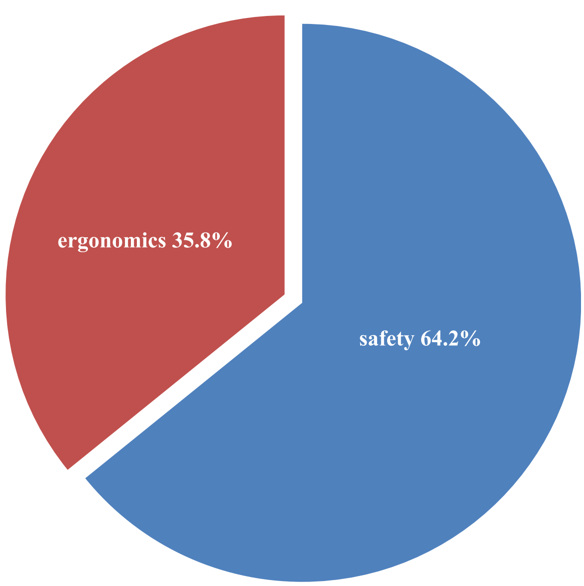


Fig. 7. Percentage distribution of papers per category.

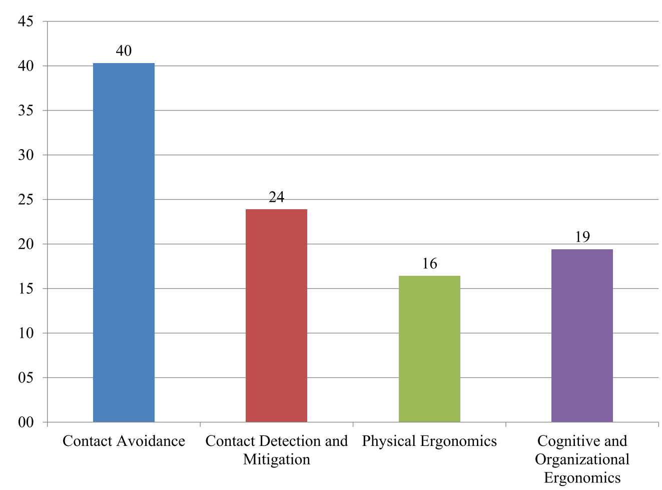


Fig. 8. Percentage distribution of papers for each cluster.

4. Discussion

In this section, we first describe and address descriptive results of our study. In a second step we discuss the results obtained from the content analysis to identify which of the found sub-clusters are or contain the most emergent research themes for the future in the context of safety and ergonomics in industrial collaborative robotics. Finally, limitations of this study are provided and discussed.

4.1. Descriptive discussion of results

The number of papers classified for each sub-cluster (including papers classified in more sub-clusters) is the following: 27 papers for Contact Avoidance, 16 papers for Contact Detection and Mitigation, 11 papers for Physical Ergonomics and 13 papers for Cognitive and Organizational Ergonomics. In total 67 papers were analyzed (including papers classified in more sub-clusters). Among these, 12 papers are classified in more than one sub-cluster. Table 5 shows the relationships of papers which are related to multiple sub-clusters:

As shown in Fig. 7, 64.2% of identified papers are related to ‘safety’ and 35.8% to ‘ergonomics’. This means that in the recent period (2015-2018) researchers invested more effort in the development of the safety aspects instead to the study of HRI ergonomics conditions.

In particular, according to Fig. 8, 40.3% of papers are related to ‘Contact Avoidance’, 23.9% of papers are related to ‘Contact Detection and Mitigation’, 19.4% are related to ‘Cognitive and Organizational Ergonomics’ and 16.4% are related to ‘Physical Ergonomics’. Considering the abovementioned percentages, the results demonstrate that the themes included in cluster 1 (Contact Avoidance) are already widely studied and therefore known and consolidated from a research point of view. The themes included in cluster 2 (Contact Detection and Mitigation) are also broadly explored and well structured, even if the

Table 6
Data about annual paper production and growth per cluster across the time (* referring to a two year time period).

No of papers per year	Contact Avoidance	% of growth	Contact Detection and Mitigation	% of growth	Physical Ergonomics	% of growth	Cognitive and Organizational Ergonomics	% of growth
2018	10	+42.9	6	+100	8	+300	5	0
2017	7	+16.7	3	−25.0	2	+100	5	+400
2016	6	+50	4	+33.3	1	/	1	−50
2015	4		3		0		2	
Average value	**6.75**	**+36.5**	**4**	**+36.1**	**2.75**	**+200**	**3.25**	**+116.7**
Sum	**27**		**16**		**11**		**13**	

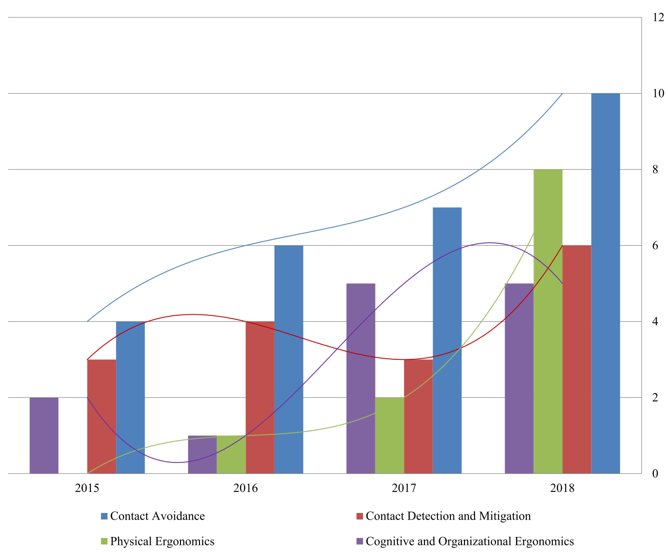


Fig. 9. Total annual paper production per cluster (* referring to a two year time period).

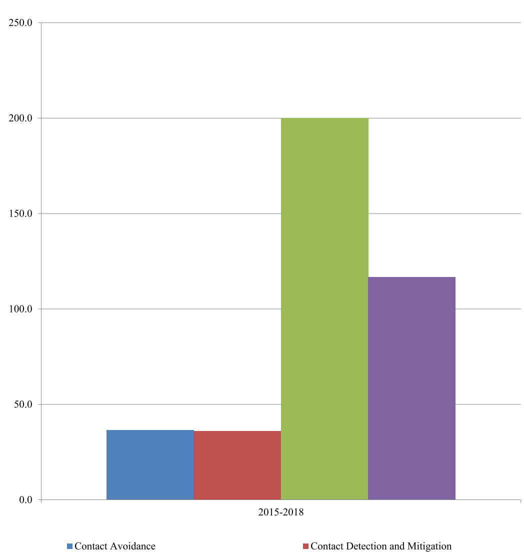


Fig. 10. Percentage of average annual paper production growth per cluster.

number of related papers is about the half respect to cluster 1. Cluster 3 (Physical Ergonomics) and cluster 4 (Cognitive and Organizational Ergonomics) are very close in terms of percentage and the relative themes are generally less investigated than the contents included in clusters related to safety.

Table 6 shows the data about the annual production of research papers and analyses the growth per cluster across the time period.

According to the total annual paper production per cluster (Fig. 9) and to the relative growth (Table 6 and Fig. 10), it is evident that all main research themes are increasing (on average) during the studied period. In particular, cluster 3 (Physical Ergonomics) presents the highest average annual growth. This is also due to the initial absence of papers in 2015. Cluster 1 (Contact Avoidance) presents a slow and quite regular increase of annual production with respect to the other clusters, even if it contains the largest value in terms of average amount of papers published per year. Cluster 4 (Cognitive and Organizational Ergonomics) presents a high average annual growth, even if it presents an initial decrease of paper production in 2016. Also in this case (as for Physical Ergonomics), the initial paper production was very limited (only one paper in 2015 and 2016). Cluster 2 (Contact Detection and Mitigation) presents a decrease of paper production in year 2017 and, in general, it has the lowest yearly average growth even if it is the second cluster in terms of average amount of published papers per year.

From the safety point of view, the high number of produced papers and the relative slow annual growth entail a consolidated and well-known knowledge for the cluster Contact Avoidance and Contact Detection and Mitigation. In addition, the data evaluation shows that the actual research tends to focus more on the prevention of unexpected and unwanted contacts (cluster 1 main themes) rather than on the reduction of the collision energy exchange (cluster 2 main themes).

From the ergonomics point of view, both physical and cognitive/organizational aspects are emerging and attractive research themes. In the first years of the studied time period, the related themes were addressed only in few works and nearly ignored. Nowadays the paper production is significant. In fact, the difference between the production of papers for both categories safety and ergonomics in the last year of the study (2018) is minimal (16 papers for safety vs. 13 papers for ergonomics). This result shows that the actual research interest in HRI ergonomics leads to a balance in the production of annual papers in both categories.

4.2. Identified emerging research fields in safety and ergonomics

Tables 7 and 8 and Figs. 11 and 12 explain the structure of clusters and sub-clusters in terms of main research themes distribution and annual paper production. In particular, Table 7 and Fig. 11 show the percentage distribution of main research themes referring to clusters and sub-clusters relationship. Table 8 and Fig. 12 explain the allocation of main research themes in terms of annual papers production referring to cluster and sub-cluster classification among the analyzed period. These data will be useful for the final analysis of every sub-cluster main research themes in order to propose a final discussion and opinion about the results in terms of importance and development during the time period.

According to the abovementioned data, the final discussion about the results of each sub-clusters analysis is reported in detail in Table 10.

This table also introduces the concept of main research themes importance, which is classified according to the distribution of works in each sub-cluster among the main research themes. This classification is presented by using five levels through different 'importance class'. Each level (and therefore each importance class) is defined through a range of percentage value which is limited by a minimum and a maximum.

Table 7
Distribution of works in each sub-cluster among the main research themes.

Sub-clusters	Motion Planning and Control	Simulation and Modelling	Artificial Intelligencce	Assistance Systems	Robot System Design	Product and Process Design	Task Scheduling Strategy	Sensor Systems for Object Tracking	Sensor Systems for Contact Management	Metrics and Tests	Safety Management	Case Studies and Applications	TOT
Contact Avoidance	12,4	3,1	3,1	3,1	0,0	0,0	0,0	9,3	0,0	0,0	9,3	1,0	**41,2**
Contact Detection and Mitigation	6,2	2,1	0,0	0,0	6,2	0,0	0,0	0,0	5,2	0,0	3,1	1,0	**23,7**
Physical Ergonomics	3,1	0,0	0,0	2,1	0,0	1,0	7,2	0,0	0,0	1,0	1,0	1,0	**16,5**
Cognitive and Organizational Ergonomics	4,1	4,1	0,0	2,1	0,0	0,0	2,1	0,0	0,0	6,2	0,0	0,0	**18,6**

Table 8
Annual paper production for each sub-cluster among the analyzed period.

Cluster	Year	Sub-clusters main themes											
		Motion Planning and Control	Simulation and Modelling	Artificial Intelligencce	Assistance Systems	Robot System Design	Product and Process Design	Task Scheduling Strategy	Sensor Systems for Object Tracking	Sensor Systems for Contact Management	Metrics and Tests	Safety Management	Case Studies and Applications
Contact Avoidance	2018	5	1	2	2	0	0	0	2	0	0	3	0
	2017	2	0	1	0	0	0	0	2	0	0	3	1
	2016	3	2	0	0	0	0	0	2	0	0	2	0
	2015	2	0	0	1	0	0	0	3	0	0	1	0
Contact Detection and Mitigation	2018	3	1	0	0	2	0	0	0	3	0	1	0
	2017	2	0	0	0	2	0	0	0	0	0	1	0
	2016	1	1	0	0	1	0	0	0	2	0	0	0
	2015	0	0	0	0	1	0	0	0	0	0	1	1
Physical Ergonomics	2018	2	0	0	2	0	1	5	0	0	1	1	0
	2017	1	0	0	0	0	0	2	0	0	0	0	0
	2016	0	0	0	0	0	0	0	0	0	0	0	1
	2015	0	0	0	0	0	0	0	0	0	0	0	0
Cognitive and Organizational Ergonomics	2018	2	1	0	2	0	0	2	0	0	0	0	0
	2017	1	2	0	0	0	0	0	0	0	4	0	0
	2016	0	1	0	0	0	0	0	0	0	1	0	0
	2015	1	0	0	0	0	0	0	0	0	1	0	0

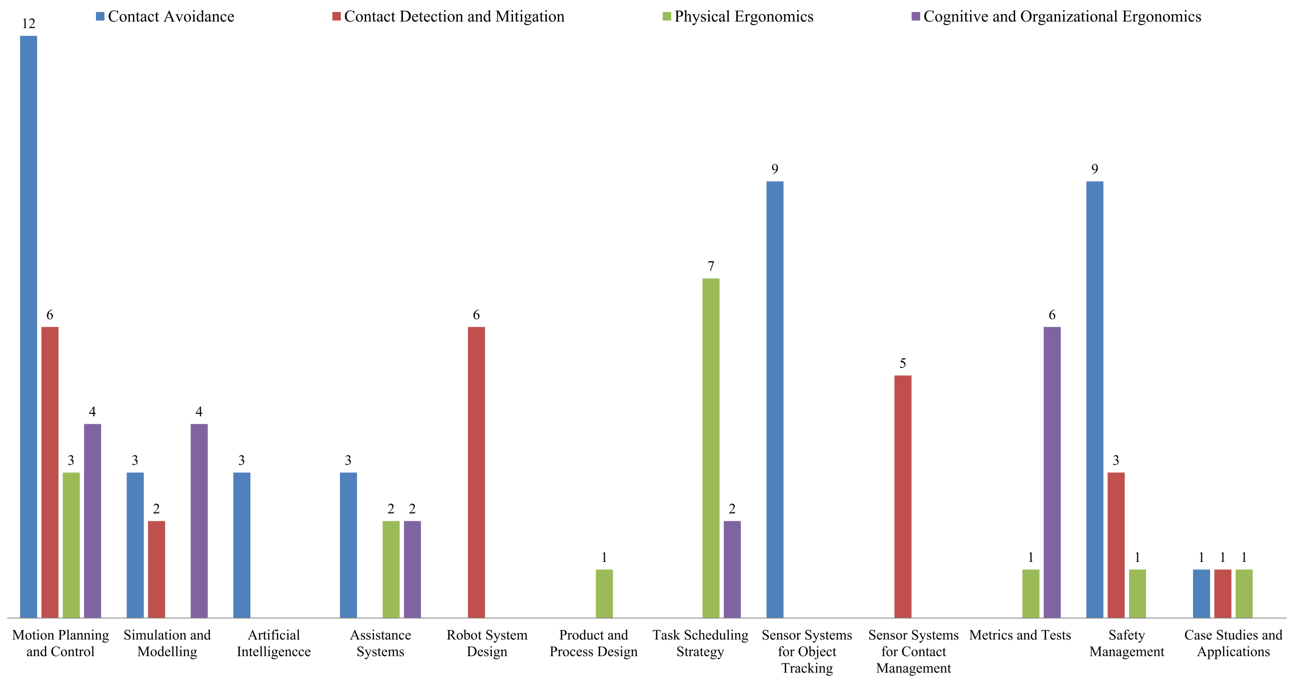


Fig. 11. Percentage of sub-cluster main themes for each cluster.

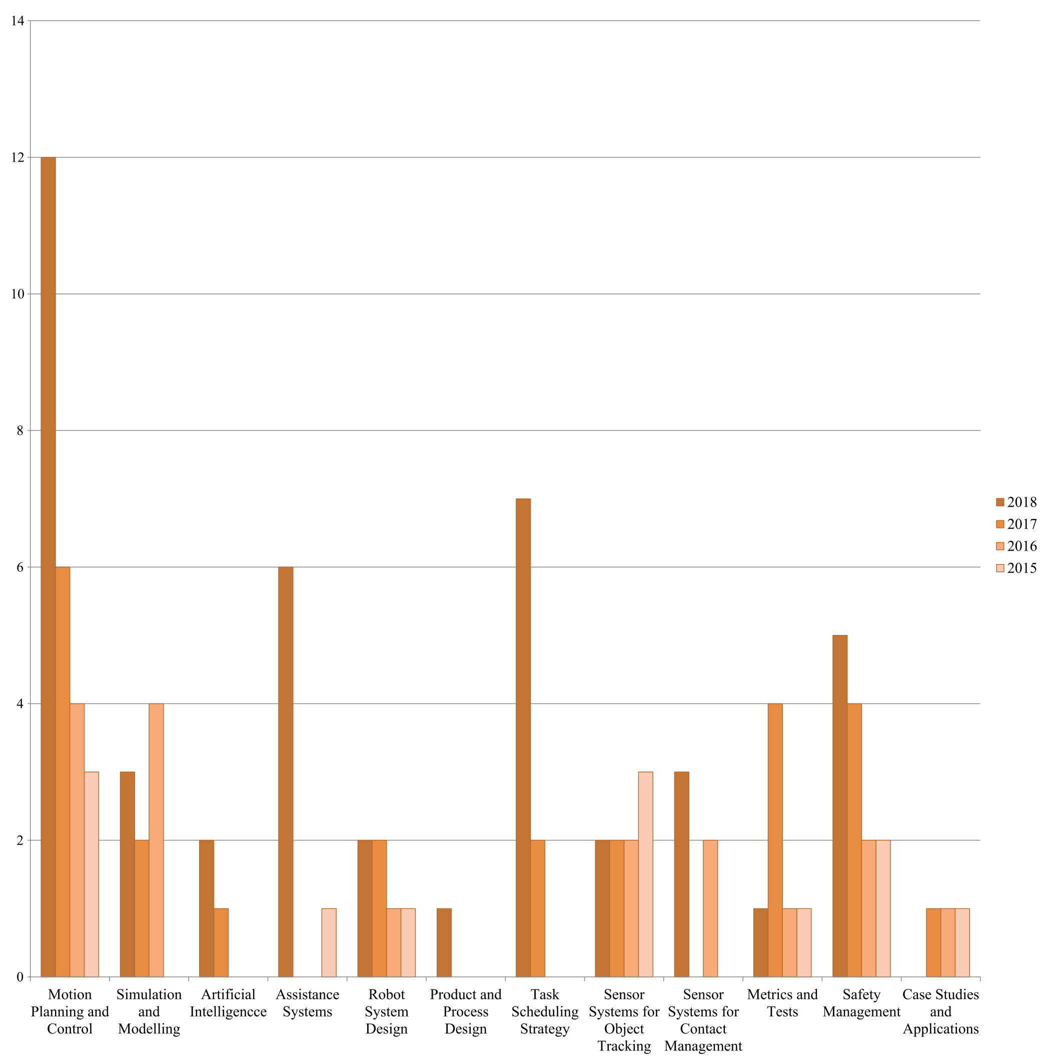


Fig. 12. Total sub-cluster main themes for each year.

Table 9
Main themes importance classification according to Table 7 data.

Level (i)	Range of importance class Max (i) %	Min (i) %	Importance class
5	12.55	10.08 [max $(i-1)$ + 0.05%]	Crucial theme
4	10.03 [min(i) + interval]	7.56 [max $(i-1)$ + 0.05%]	Very important theme
3	7.51 [min(i) + interval]	5.04 [max $(i-1)$ + 0.05%]	Important theme
2	4.99 [min(i) + interval]	2.52 [max $(i-1)$ + 0.05%]	Moderately important theme
1	2.47 [min(i) + interval]	0	Irrelevant theme

These thresholds are calculated as explained in Table 9 according to a certain interval. The calculation of the interval is the following:

$$Interval = \frac{\max\ \%\ value^{*} -- \min\ \%\ value^{*}}{nr\ of\ importance\ classes} = \frac{12.4\% - 0\%}{5} = 2.47\ \frac{[\%]}{[Importance\ class]}$$

(* = according to Table 7 – Distribution of works in each sub-cluster among the main research themes)

The number of levels is equal to five since it is a reasonable value for a proper distinction between different importance classes (a value which is lower than five will provide an approximate classification, a value higher than five will provide a too detailed classification referring to the purpose of the analysis).

For the calculation of the Min (i) percentage, a constant value of 0.05% for each importance class is added to the previous Max (i) (except for the first Min (i) which is equal to zero). This constant is reasonable small enough to allow the definition of a new importance class without afflicting the influence of the interval value to the level calculation. Finally, Table 11 gives a general overview and comparison about the main results.

4.3. Limitations

Following, the main limitations of the adopted SLR search approach and the related inclusion/exclusion criteria are explained:

(a) **Time period:** even if the concept of industrial HRI dates back to the nineties, collaborative robots were introduced to the market after the beginning of the Industry 4.0 era and therefore after 2011 [1]. For a broader analysis, it could be useful to extend the review also including the time period which starts from 2011, in order to include the earliest research trends. As in this research we focus on the analysis of emerging research trends in the last few years we limited the period of study to the years from 2015 to 2018. In fact, according to Scopus data, the annual paper production related to safety and ergonomics in HRI is starting to grow significantly from 2015, which is the starting year of the analyzed period.

(b) **Document type:** in order to have only high quality results, the proposed method focused only on journal-type documents. Despite, the inclusion of conference papers could add additional information about recent inputs from research, since the journal publication process is usually quite structured and therefore time-consuming. As a consequence, it might be that in this work we did not consider the latest research studies already published only in conference proceedings and not yet published in high quality journal articles. For further analysis, the papers presented in relevant conferences should be consulted. Following, there is a list of some important examples: Conference on Flexible Automation and Intelligent Manufacturing (FAIM), CIRP Conference on Manufacturing Systems (CMS), International Conference on Human–robot Interaction (HRI), International Conference on Robot and Human Interactive Communication (RO-MAN).

(c) **Subject area:** the main selected subject areas in this study are 'Engineering' and 'Computer Science' as we focus on the latest research trends in the field of industrial applications of HRC. Nevertheless, it is possible to enlarge the review by adding other research areas such as Medicine or Mathematics. This might improve the number of results, even if the percentage of pertinent themes would probably be rather restricted. In addition, since some relevant industry-related publications about ergonomics and human factors are published in non-technical journals, we want to mention that these works may not be considered into this SLR.

(d) **SMEs factor:** collaborative robotics could be particularly helpful for small and medium-sized enterprises (SMEs). For this reason, future reviews could include the term SMEs as a search keyword in the initial search workflow. After a first trial we identified only very few works in the database Scopus for the time period 2015–2018 without setting any further exclusion criteria like subject area or document type. Therefore, we decided to not limit our study only to works related to SMEs, also because very often general works are applicable in both large companies and SMEs.

(e) **Categorization:** based on the research question and the content analysis, the research team identified two main categories (safety and ergonomics), four clusters (Contact Avoidance, Contact Detection and Mitigation, Physical Ergonomics and cognitive/organization ergonomics) and 11 sub-clusters (see also Fig. 2). This categorization and the following identification of the main research themes in recent literature have been defined by a research team consisting of three researchers in order to obtain and present a situation that is as objective as possible. There is the possibility that other researchers might define the categorization in a slightly modified way then used in this work.

4.4. Future developments and open issues

Following, a proposal for future research developments is presented by considering the most important and promising research themes identified in Tables 10 and 11 for every cluster.

4.4.1. Safety

The role of safety in HRI should be to protect the operators from the consequences of unexpected and unwanted collisions between human body parts and robot systems and/or workspaces elements by maintaining proper performance of production systems at the same time (Table 12).

Contact avoidance: the most important and promising research themes for Contact Avoidance are Motion Planning and Control (crucial theme), Sensor Systems for Object Tracking (very important theme) and Safety Management (very important theme). In general, this result confirms the general trend to develop safety systems which focus even more on the safeguard of operators by adopting prevention techniques. For this reason, a proper and coordinated integration between the development of vision systems, robot control and trajectory planning methodologies will be essential. The Safety Management part will be very important to support the application and the evaluation of the proposed safety measures. These aspects are fundamental for a better prediction of collisions and therefore for the minimization of the probability of occurrence.

Contact detection and mitigation: the most important and promising research themes for Contact Detection and Mitigation are Motion Planning and Control (important theme), Robot System Design (important theme) and sensor system for contact management (important theme). Also in this case, there is a natural correlation between the development of these research themes. Actually, in order to improve the safety measures based on protection techniques, there is the need to work jointly on the development of the features related to the

Table 10
Final classification of sub-cluster relevance according to the distribution of works in each sub-cluster among the main research themes and to the distribution of works in each sub-cluster among the analyzed period.

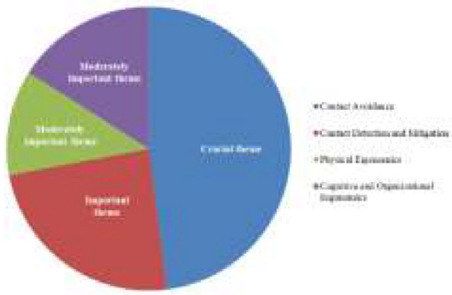
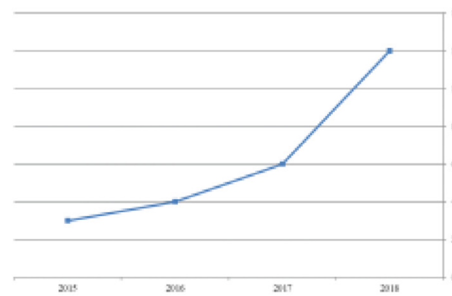
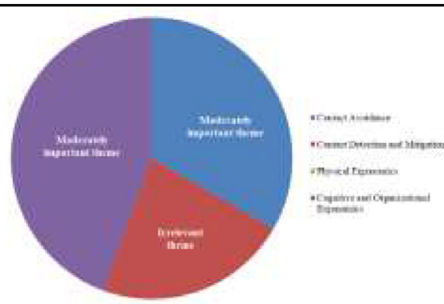
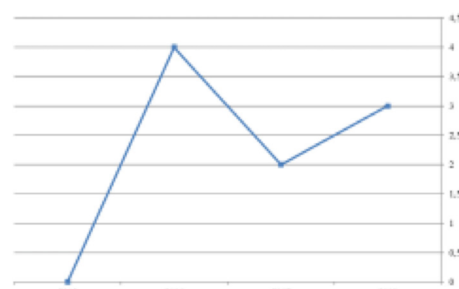
Sub-cluster	Main themes importance		Development during the time period
Motion Planning and Control			
	Contact Avoidance	Crucial theme (12.4%)	Rapid and continuous increase during all the period. Very high amount of papers produced during the time period.
	Contact Detection and Mitigation	Important theme (6.2%)	
	Physical Ergonomics	Moderately important theme (3.1%)	
	Cognitive and Organizational Ergonomics	Moderately important theme (4.1%)	
	Final judgment: widespread, interesting and extensively discussed theme especially for Contact Avoidance and Contact Detection and Mitigation clusters.		
Simulation and Modelling			
	Contact Avoidance	Moderately important theme (3.1%)	No papers produced in 2015. After 2016, slow decrease and flat trend during the rest of the period. Fair amount of papers produced during the time period.
	Contact Detection and Mitigation	Irrelevant theme (2.1%)	
	Physical Ergonomics	Irrelevant theme (0%)	
	Cognitive and Organizational Ergonomics	Moderately important theme (4.1%)	

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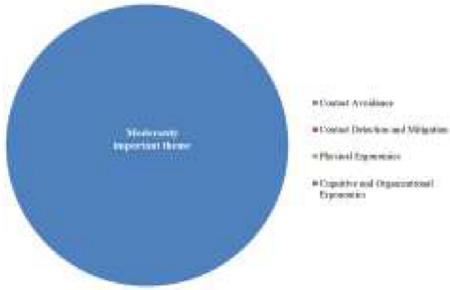
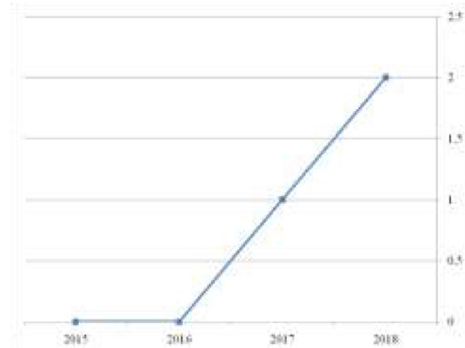
Table 10 (*continued*)

Final judgment: recent and quite consolidated theme especially for Contact Avoidance and Cognitive and Organizational Ergonomics

Artificial Intelligence



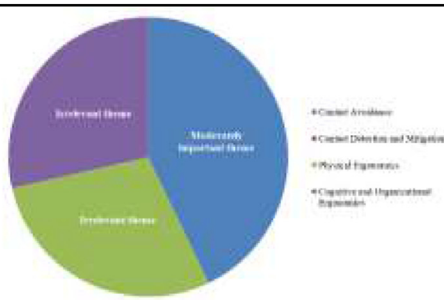
Contact Avoidance	Moderately important theme (3.1%)
Contact Detection and Mitigation	Irrelevant theme (0%)
Physical Ergonomics	Irrelevant theme (0%)
Cognitive and Organizational Ergonomics	Irrelevant theme (0%)



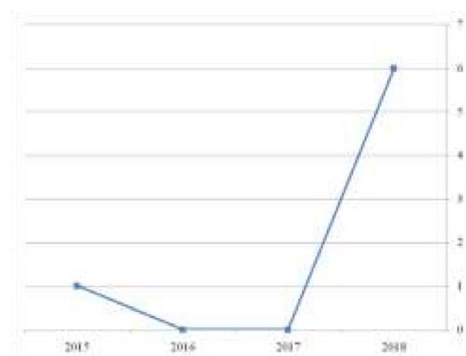
No papers produced until 2017 – moderate increase during the rest of the period. Very low amount of papers produced during the time period.

Final judgment: emerging, recent, not yet consolidated and uncertain theme exclusively for Contact Avoidance

Assistance Systems



Contact Avoidance	Moderately important theme (3.1%)
Contact Detection and Mitigation	Irrelevant theme (0%)
Physical Ergonomics	Irrelevant theme (2.1%)
Cognitive and Organizational Ergonomics	Irrelevant theme (2.1%)



Only one paper produced in 2015 – six papers produced in 2018 (high increase) – no papers produced in the meantime. Fair amount of papers produced during the time period.

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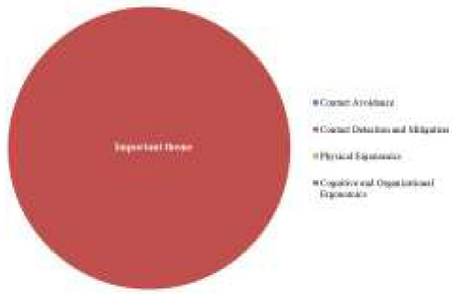
Table 10 (*continued*)

Final judgment: emerging and promising theme especially for Contact Avoidance

Robot System Design

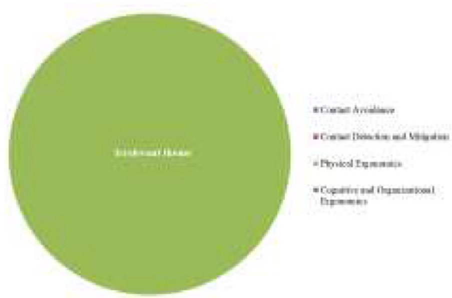


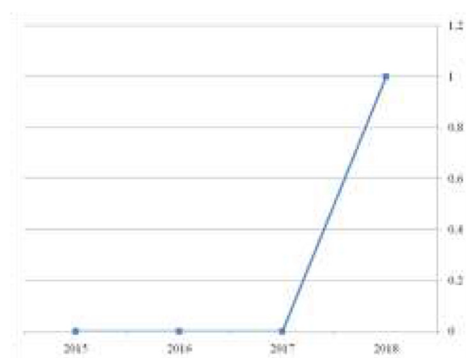
Contact Avoidance	Irrelevant theme (0%)
Contact Detection and Mitigation	Important theme (6.2%)
Physical Ergonomics	Irrelevant theme (0%)
Cognitive and Organizational Ergonomics	Irrelevant theme (0%)

Constant and flat trend during the time period Very low amount of papers produced during the time period.

Final judgment: quite consolidated and moderately developed theme exclusively for Contact Detection and Mitigation

Product and Process Design





Contact Avoidance	Irrelevant theme (0%)
Contact Detection and Mitigation	Irrelevant theme (0%)
Physical Ergonomics	Irrelevant theme (1.0%)
Cognitive and Organizational Ergonomics	Irrelevant theme (0%)

Only one paper was produced in 2018. Minimum amount of paper produced during the time period.

Final judgment: emerging, very recent, not yet consolidated and uncertain theme

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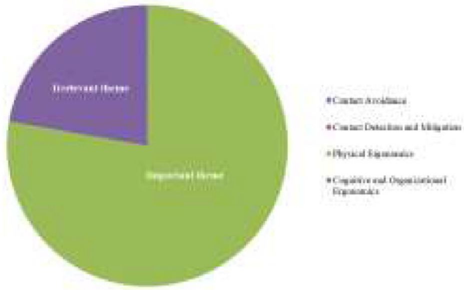
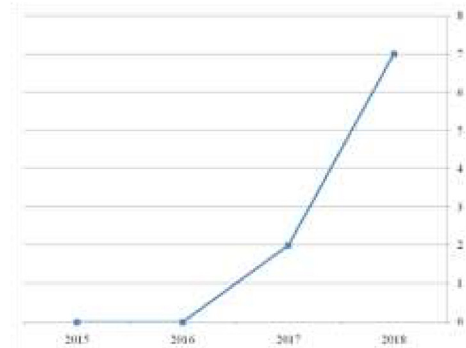
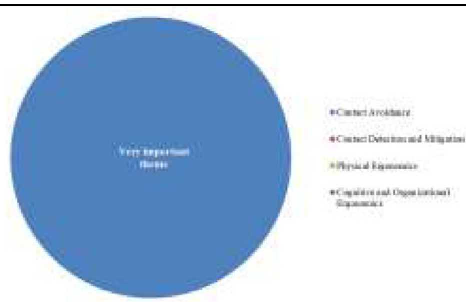
Table 10 (*continued*)

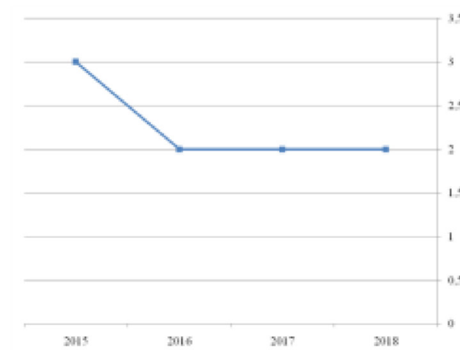




Task Scheduling Strategy	Contact Avoidance	Irrelevant theme (0%)	Rapid and continuous increase during 2017/2018 period – no papers produced in the 2015/2016 period. High amount of papers produced during the time period.
	Contact Detection and Mitigation	Irrelevant theme (0%)	
	Physical Ergonomics	Important theme (7.2%)	
	Cognitive and Organizational Ergonomics	Irrelevant theme (2.1%)	

Final judgment: emerging, recent and promising theme especially for Physical Ergonomics





Sensor Systems for Object Tacking	Contact Avoidance	Very important theme (9.3%)	Slow decrease and flat trend during the rest of the period after 2015. High amount of papers produced during the time period.
	Contact Detection and Mitigation	Irrelevant theme (0%)	
	Physical Ergonomics	Irrelevant theme (0%)	
	Cognitive and Organizational Ergonomics	Irrelevant theme (0%)	

Final judgment: consolidated and mature theme exclusively for Contact Avoidance

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Table 10 (*continued*)

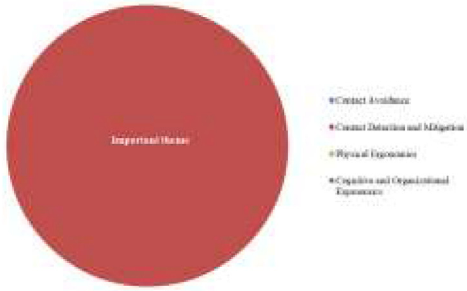
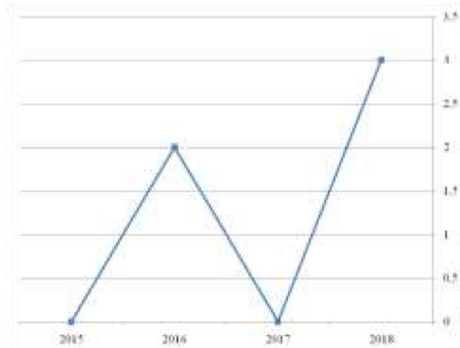
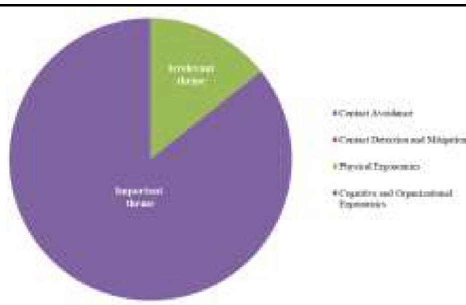
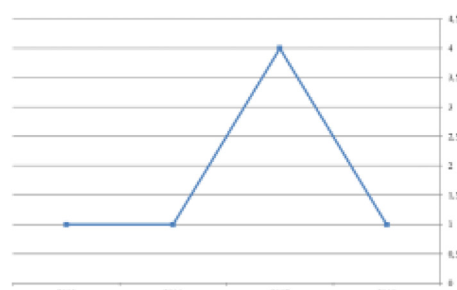
Sensor Systems for Contact Management			
	Contact Avoidance	Irrelevant theme (0%)	Irregular and fluctuating trend during the time period – no papers produced in 2015 and 2017. Fair amount of papers produced during the time period.
	Contact Detection and Mitigation	Important theme (5.2%)	
	Physical Ergonomics	Irrelevant theme (0%)	
	Cognitive and Organizational Ergonomics	Irrelevant theme (0%)	
	Final judgment: irregular, high potential and uncertain theme exclusively for Contact Detection and Mitigation		
Metrics and Tests			
	Contact Avoidance	Irrelevant theme (0%)	Irregular trend during the time period characterized by a peak of paper production in 2017. Notable amount of papers produced during the time period,
	Contact Detection and Mitigation	Irrelevant theme (0%)	
	Physical Ergonomics	Irrelevant theme (1.0%)	
	Cognitive and Organizational Ergonomics	Important theme (6.2%)	
	Final judgment: irregular and uncertain theme especially for Cognitive and Organizational Ergonomics		

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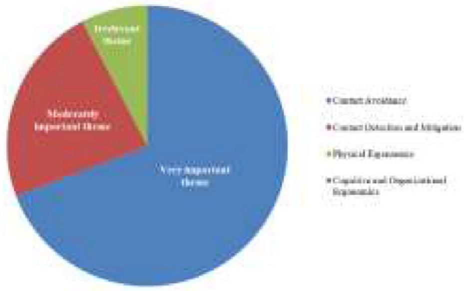
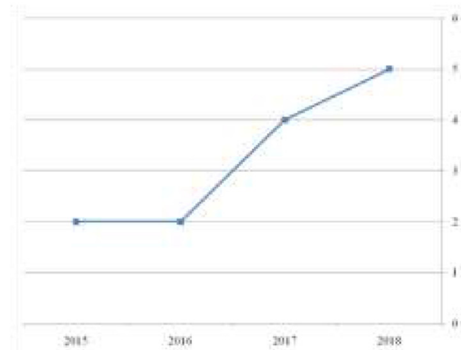
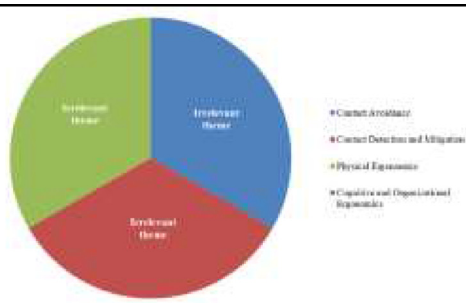
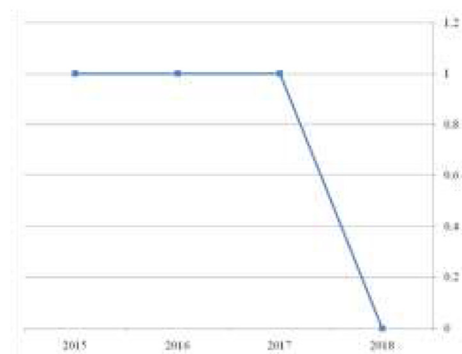
Table 10 (*continued*)

Safety Management			
	Contact Avoidance	Very important theme (9.3%)	Slow and continuous increase during 2017/2018 period – constant trend during 2015/2016 period. High amount of papers produced during the time period.
	Contact Detection and Mitigation	Moderately important theme (3.1%)	
	Physical Ergonomics	Irrelevant theme (1.0%)	
	Cognitive and Organizational Ergonomics	Irrelevant theme (0%)	
	Final judgment: widespread, interesting and discussed theme especially for Contact Avoidance and Contact Detection and Mitigation		
Case Studies and Applications			
	Contact Avoidance	Irrelevant theme (1.0%)	Constant trend during 2015-2017 period. No papers produced in 2018. Very low amount of papers produced during the time period.
	Contact Detection and Mitigation	Irrelevant theme (1.0%)	
	Physical Ergonomics	Irrelevant theme (1.0%)	
	Cognitive and Organizational Ergonomics	Irrelevant theme (0%)	
	Final judgment: not yet widely considered and uncertain theme (in general, it is difficult to present high-quality research studies which mainly focus only on the description of a case study)		

robot hardware, the sensor systems for the contact detection and elaboration as well as on the trajectory planning and robot control. These aspects are fundamental for a better management of collision and therefore for the minimization of the related effects.

4.4.2. Ergonomics

The role of ergonomics in HRI should be to support humans in the reduction of work-related biomechanical and cognitive overload without introducing new hazards for the health and safety of the operators (e.g. work-related stress which potentially could arise from the interaction with the robot systems).

Physical Ergonomics: the most important and promising research themes for Physical Ergonomics are Task Scheduling (important theme) and Motion Planning and Control (moderately important theme). In general, these results strengthen the concept of human-centered workspaces supported by smart automation systems. In particular, future research should focus on the development of adaptive and real-time Task Scheduling and Motion Planning and Control methodologies. These should allow a reduction of physical workload by changing the work cycle and the robot systems performance according to the operators physical conditions (e.g. individual anthropometric features, age, gender, dominant limb, particular physical limitations or disabilities, fatigue etc.). This condition is a perfect example of implementation of sustainable production systems. In fact, it should improve the operators' wellbeing as well as the possibility to include elderly workforce or personnel with temporal or permanent disability. Of course, this means to provide to the production system a substantial amount of (real-time) personal data about the operators' psychophysical conditions.

Cognitive ergonomics: the most important and promising research

Table 11
Summary about the level of importance of the research themes for each cluster and sub-cluster.

Sub-clusters	Motion Planning and Control	Simulation and Modelling	Artificial Intelligence	Assistance Systems	Robot System Design	Product and Process Design	Task Scheduling Strategy	Sensor Systems for Object Tracking	Sensor Systems for Contact Management	Metrics and Tests	Safety Management	Case Studies and Applications
Contact Avoidance	Crucial theme	Moderately important theme	Moderately important theme	Moderately important theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Very important theme	Irrelevant theme	Irrelevant theme	Very important theme	Irrelevant theme
Contact Detection and Mitigation	Important theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Important theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Important theme	Irrelevant theme	Moderately important theme	Irrelevant theme
Physical Ergonomics	Moderately important theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Important theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Irrelevant theme
Cognitive and Organizational Ergonomics	Moderately important theme	Moderately important theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Irrelevant theme	Important theme	Irrelevant theme	Irrelevant theme

themes for cognitive ergonomics are Metrics and Tests (important theme), Motion Planning and Control (moderately important theme) and Simulation and Modelling (moderately important theme). In general, the cognitive part should also focus on the minimization of work-related psychosocial risks which could potentially arise from the sharing of activities and workspaces. Another important part will be the acceptability of the robot systems by the human coworkers. In fact, a more or less closed interaction produces several advantages but also introduces new forms of discomfort for the operators at the same time. In this context and according to the results, it could be important to provide methodologies for collaborative systems evaluation and tests. This could be crucial for the identification and mitigation of potential sources of psychosocial risks. In addition, the design of the main features and performance related to collaborative systems (including the robot motion and control) should consider these aspects. Simulations and model will be very important to support and validate the choices.

5. Conclusions

According to the aims of this work, the emerging research challenges and research fields about safety and ergonomics in industrial collaborative robotics were identified and analyzed based on the development of publications over time (annual growth). The main limitations and critical issues of the adopted search approach are provided and explained by proposing some useful suggestions for future investigations or reviews. First of all, the results show that there is some vagueness and uncertainty in the definition of safety or ergonomics in the research world. In fact, there are different works which were initially founded by using a specific keyword (safety or ergonomics or human factors), even if the real content of related papers deals with the other topics.

The results show that the most developed research category is safety, even if ergonomics has been growing significantly in the last two years (especially the cognitive and organizational part). In particular, results show that the majority of high-level (of importance) themes are more related to safety aspects instead of ergonomics. Referring to safety works, there is a higher interest in prevention (which studies safety measures that aim to operate before potential human–robot contacts occur) than in protection (which studies safety measures that aim to minimize the effects of human–robot contacts after the physical interaction occurs). Collision avoidance is the largest cluster characterized by a slow, but constant, paper production rate. Nevertheless, even if ergonomics presented the highest paper production in the last years, the related themes are considered emerging but not yet mature In addition, there is a disequilibrium between the current development of safety (especially for collision avoidance) and ergonomics (both physical, cognitive and organizational), which means that the former aspects may have a greater potential for further developments than the latter in the near future. Taking into account that the industrial collaborative robot market is continuously growing [64], near future collision avoidance systems might allow a general improvement of robots performance while maintaining proper levels of safety. This scenario could generate collaborative production systems where operators are supposed to work even closer to high performance and safe robots. On the other hand, this situation could harm the psychological part of the collaboration and, as a consequence, the efficiency of the production system. The reason is that humans might not trust and accept advanced robotic systems without likewise ergonomics developments in terms of cognitive and organizational knowledge and support.

In other words, in the near future it will be necessary to catalyze the research effort in the balancing of the developments of different research areas related to HRI. This will be necessary to create genuine and human-oriented potentials and not technological barriers. For these reasons, future developments should focus on the alignment of HRI safety and ergonomics research themes, especially in terms of sustainability, operator well-being and related human-centered design, social

Table 12
Description of papers encoding, processing and final classification in Step 4 (SAF = Safety; ERG = Ergonomics; SAF/ERG = Safety and Ergonomics).

Authors	Title	Year	Scopus last keyword	Relevance	Final classification
Michalos G., Spiliotopoulos J., Makris S., Chryssolouris G.	A method for planning human robot shared tasks	2018	ERG	Relevant	ERG
Rajnathsing H., Li C.	A neural network based monitoring system for Safety in shared work-space human–robot collaboration	2018	SAF	Relevant	SAF
Long P., Chevallereauo C., Chablat D., Girin A.	An industrial security system for human–robot coexistence	2018	SAF	Relevant	SAF/ERG
Kim W., Lee J., Peternel L., Tsagarakis N., Ajoudani A.	Anticipatory Robot Assistance for the Prevention of Human Static Joint Overloading in Human–robot Collaboration	2018	ERG	Not relevant - 2° round of screening	
Di Castro M., Ferre M., Masi A.	CERNTAURO: A modular architecture for robotic inspection and telemanipulation in harsh and Semi-Structured environments	2018	SAF	Not relevant - 1° round of screening	
Campbell K., Weihl C.	Cobots: Man and machine team up for workplace productivity; industry leaders discuss how human–robot collaboration is shaping the future of manufacturing	2018	SAF	Not relevant - 1° round of screening	
Sadrfaridpour B., Wang Y.	Collaborative Assembly in Hybrid Manufacturing Cells: An Integrated Framework for Human–robot Interaction	2018	SAF	Relevant	ERG
Ren T., Dong Y., Wu D., Chen K.	Collision detection and identification for robot manipulators based on extended state observer	2018	SAF	Relevant	SAF
Wang P., Liu H., Wang L., Gao R.X.	Deep learning-based human motion recognition for predictive context-aware human–robot collaboration	2018	SAF	Not relevant - 1° round of screening	
Liang X., Cheong H., Sun Y., Guo J., Chui C.K., Yeow C.-H.	Design, Characterization, and Implementation of a Two-DOF Fabric-Based Soft Robotic Arm	2018	SAF	Not relevant - 2° round of screening	
Hansen C., Gosselin F., Ben Mansour K., Devos P., Marin F.	Design-validation of a hand exoskeleton using musculoskeletal modeling	2018	ERG	Not relevant - 2° round of screening	
Pang G., Deng J., Wang F., Zhang J., Pang Z., Yang G.	Development of flexible robot skin for safe and natural human–robot collaboration	2018	SAF	Relevant	SAF
Roveda L., Iannacci N., Tosatti L.M.	Discrete-Time Formulation for Optimal Impact Control in Interaction Tasks	2018	SAF	Relevant	SAF
Unhelkar V.V., Lasota P.A., Tyroller Q., Buhai R.-D., Marceau L., Deml B., Shah J.A.	Human-Aware Robotic Assistant for Collaborative Assembly: Integrating Human Motion Prediction with Planning in Time	2018	SAF	Not relevant - 2° round of screening	
Merckaert K., De Beir A., Adriaens N., El Makrini I., Van Ham R., Vanderborght B.	Independent load carrying and measurement manipulator robot arm for improved payload to mass ratio	2018	SAF	Relevant	SAF
Dean-Leon E., Ramirez-Amaro K., Bergner F., Dianov I., Cheng G.	Integration of Robotic Technologies for Rapidly Deployable Robots	2018	SAF	Relevant	SAF
Rahman S.M.M., Wang Y.	Mutual trust-based subtask allocation for human–robot collaboration in flexible lightweight assembly in manufacturing	2018	SAF	Relevant	ERG
Bänziger T., Kunz A., Wegener K.	Optimizing human–robot task allocation using a simulation tool based on standardized work descriptions	2018	ERG	Not relevant - 2° round of screening	
Pearce M., Mutlu B., Shah J., Radwin R.	Optimizing Makespan and Ergonomics in Integrating Collaborative Robots into Manufacturing Processes	2018	ERG	Relevant	ERG
Pereira A., Althoff M.	Over approximative Human Arm Occupancy Prediction for Collision Avoidance	2018	SAF	Relevant	SAF
Asadi E., Li B., Chen I.-M.	Pictobot: A Cooperative Painting Robot for Interior Finishing of Industrial Developments	2018	SAF	Not relevant - 1° round of screening	
Matsas E., Vosniakos G.-C., Batras D.	Prototyping proactive and adaptive techniques for human–robot collaboration in manufacturing using virtual reality	2018	SAF	Relevant	SAF/ERG
Peternel L., Petrič T., Babič J.	Robotic assembly solution by human-in-the-loop teaching method based on real-time stiffness modulation	2018	SAF	Not relevant - 2° round of screening	
Weitschat R., Aschemann H.	Safe and Efficient Human–robot Collaboration Part II: Optimal Generalized Human-in-the-Loop Real-Time Motion Generation	2018	SAF	Not relevant - 2° round of screening	
Heydaryan S., Bedolla J.S., Belingardi G.	Safety design and development of a human–robot collaboration assembly process in the automotive industry	2018	ERG	Relevant	SAF/ERG
Heydaryan S., Bedolla J.S., Belingardi G.	Safety design and development of a human–robot collaboration assembly process in the automotive industry	2018	SAF	Double file	
Lippi M., Marino A.	Safety in human-multi robot collaborative scenarios: a trajectory scaling approach	2018	SAF	Relevant	SAF
Michalos G., Kousi N., Karagiannis P., Gkournelos C., Dimoulas K., Koukas S., Mparis K., Papavasileiou A., Makris S.	Seamless human robot collaborative assembly – An automotive case study	2018	SAF	Relevant	SAF
Khalid A., Kirisci P., Khan Z.H., Ghrairi Z., Thoben K.-D., Pannek J.	Security framework for industrial collaborative robotic cyber-physical systems	2018	SAF	Not relevant - 1° round of screening	
Villani V., Pini F., Leali F., Secchi C.	Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications	2018	SAF	Not relevant - 2° round of screening	

(*continued on next page*)

Table 12 (*continued*)

Authors	Title	Year	Scopus last keyword	Relevance	Final classification
Dannapfel M., Bruggräf P., Bertram S., Förstmann R., Riegauf A.	Systematic planning approach for heavy-duty human–robot cooperation in automotive flow assembly	2018	ERG	Relevant	SAF/ERG
Dannapfel M., Bruggräf P., Bertram S., Förstmann R., Riegauf A.	Systematic planning approach for heavy-duty human–robot cooperation in automotive flow assembly	2018	SAF	Double file	
Tang G., Webb P.	The Design and Evaluation of an Ergonomic Contactless Gesture Control System for Industrial Robots	2018	ERG	Relevant	ERG
Pransky J.	The Pransky interview: Dr Aaron Edsinger, CEO and cofounder at Hello Robot Inc	2018	SAF	Not relevant - 1° round of screening	
Ragaglia M., Zanchettin A.M., Rocco P.	Trajectory generation algorithm for safe human–robot collaboration based on multiple depth sensor measurements	2018	SAF	Relevant	SAF
Xia F., Campi F., Bahreyni B.	Tri-Mode Capacitive Proximity Detection Towards Improved Safety in Industrial Robotics	2018	SAF	Relevant	SAF
Liau Y.Y., Ryu K.	Visual inspection based on machine vision system for smart injection molding	2018	ERG	Not relevant - 2° round of screening	
Vemula B., Matthias B., Ahmad A.	A design metric for safety assessment of industrial robot design suitable for power- and force-limited collaborative operation	2018	SAF	Relevant	SAF
Maurice P., Huber M.E., Hogan N., Sternad D.	Velocity-Curvature Patterns Limit Human–robot Physical Interaction	2018	ERG	Relevant	ERG
Bdiwi M., Pfeifer M., Sterzing A.	A new strategy for ensuring human Safety during various levels of interaction with industrial robots	2017	SAF	Relevant	SAF
Mokaram S., Aitken J.M., Martinez-Hernandez U., Eimontaite I., Cameron D., Rolph J., Gwilt I., McAree O., Law J.	A ROS-integrated API for the KUKA LBR iiwa collaborative robot	2017	SAF	Not relevant - 1° round of screening	
Atashzar S.F., Polushin I.G., Patel R.V.	A Small-Gain Approach for Nonpassive Bilateral Telerobotic Rehabilitation: Stability Analysis and Controller Synthesis	2017	SAF	Not relevant - 2° round of screening	
Mohammed A., Schmidt B., Wang L.	Active collision avoidance for human–robot collaboration driven by vision sensors	2017	SAF	Not relevant - 2° round of screening	
Sadik A.R., Urban B.	An ontology-based approach to enable knowledge representation and reasoning in Worker-Cobot agile manufacturing	2017	SAF	Not relevant - 1° round of screening	
Rengevic A., Kumicakova D., Kuric I., Tlach V., Drozdziel P.	Approaches to the computer vision system proposal on purposes of objects recognition within the human–robot shared workspace collaboration	2017	SAF	Relevant	SAF
Brending S., Lawo M., Pannek J., Sprodowski T., Zeising P., Zimmermann D.	Certifiable Software Architecture for Human Robot Collaboration in Industrial Production Environments	2017	SAF	Relevant	SAF
Faber M., Mertens A., Schlick C.M.	Cognition-enhanced assembly sequence planning for ergonomic and productive human–robot collaboration in self-optimizing assembly cells	2017	ERG	Relevant	ERG
Bostelman R., Messina E., Foufou S.	Cross-industry standard test method developments: from manufacturing to wearable robots	2017	SAF	Not relevant - 1° round of screening	
Li S., Li J., Li S.-Q., Huang Z.-L.	Design and implementation of robot serial integrated rotary joint with Safety compliance	2017	SAF	Relevant	SAF
Matsas E., Vosniakos G.-C.	Design of a virtual reality training system for human–robot collaboration in manufacturing tasks	2017	SAF	Relevant	ERG
Bogue R.	Detecting humans in the robot workspace	2017	SAF	Not relevant - 2° round of screening	
Makris S., Tsarouchi P., Matthaiakis A.-S., Athanasatos A., Chatzigeorgiou X., Stefos M., Giavridis K., Aivaliotis S.	Dual arm robot in cooperation with humans for flexible assembly	2017	SAF	Relevant	SAF/ERG
Koppenborg M., Nickel P., Naber B., Lungfiel A., Huelke M.	Effects of movement speed and predictability in human–robot collaboration	2017	SAF	Relevant	ERG
Spirescu M., Dumitru S., Constantinesu A., Badea C.	Human – Robots safe cooperation in an integrated approach	2017	SAF	Relevant	SAF
Maurtua I., Ibarguren A., Kildal J., Susperregi L., Sierra B.	Human–robot collaboration in industrial applications: Safety, interaction and trust	2017	SAF	Relevant	ERG
Ustunel Z., Gunduz T.	Human–robot collaboration on an assembly work with extended cognition approach	2017	ERG	Not relevant - 2° round of screening	
Ustunel Z., Gunduz T.	Human–robot collaboration on an assembly work with extended cognition approach	2017	SAF	Double file	
Meziane R., Otis M.J.-D., Ezzaidi H.	Human–robot collaboration while sharing production activities in dynamic environment: SPADER system	2017	SAF	Relevant	SAF
Gil-Vilda F., Sune A., Yagüe-Fabra J.A., Crespo C., Serrano H.	Integration of a collaborative robot in a U-shaped production line: a real case study	2017	SAF	Not relevant - 1° round of screening	
Dombrowski U., Stefanak T., Perret J.	Interactive Simulation of Human–robot Collaboration Using a Force Feedback Device	2017	ERG	Not relevant - 2° round of screening	
Dombrowski U., Stefanak T., Perret J.	Interactive Simulation of Human–robot Collaboration Using a Force Feedback Device	2017	SAF	Double file	

(*continued on next page*)

Table 12 (*continued*)

Authors	Title	Year	Scopus last keyword	Relevance	Final classification
Kimmel M., Hirche S.	Invariance control for safe human–robot interaction in dynamic environments	2017	SAF	Relevant	SAF
Spada S., Ghibaudo L., Gilotta S., Gastaldi L., Cavatorta M.P.	Investigation into the Applicability of a Passive Upper-limb Exoskeleton in Automotive Industry	2017	ERG	Not relevant - 2° round of screening	
Pellegrinelli S., Orlandini A., Pedrocchi N., Umbrico A., Tolio T.	Motion planning and scheduling for human and industrial-robot collaboration	2017	SAF	Not relevant - 1° round of screening	
Tsarouchi P., Michalos G., Makris S., Athanasatos T., Dimoulas K., Chryssolouris G.	On a human–robot workplace design and task allocation system	2017	ERG	Not relevant - 2° round of screening	
Vogel C., Walter C., Elkmann N.	Safeguarding and Supporting Future Human–robot Cooperative Manufacturing Processes by a Projection- and Camera-based Technology	2017	SAF	Not relevant - 2° round of screening	
Saenz J., Vogel C., Penzlin F., Elkmann N.	Safeguarding Collaborative Mobile Manipulators - Evaluation of the VALERI Workspace Monitoring System	2017	SAF	Not relevant - 2° round of screening	
Guo J., Bai C., Chen C.	Sequence planning for human and robot cooperative assembly of large space truss structures	2017	ERG	Not relevant - 2° round of screening	
Charalambous G., Fletcher S.R., Webb P.	The development of a Human Factors Readiness Level tool for implementing industrial human–robot collaboration	2017	SAF	Relevant	ERG
Vivo G., Zanella A., Tokcalar O., Michalos G.	The ROBO-PARTNER EC Project: CRF Activities and Automotive Scenarios	2017	SAF	Not relevant - 1° round of screening	
El Makrini I., Rodriguez-Guerrero C., Lefeber D., Vanderborght B.	The variable boundary layer sliding mode control: A safe and performant control for compliant joint manipulators	2017	SAF	Not relevant - 2° round of screening	
Labrecque P.D., Laliberté T., Foucault S., Abdallah M.E., Gosselin C.	UMan: A low-impedance manipulator for human–robot cooperation based on underactuated redundancy	2017	SAF	Relevant	SAF
Robla-Gomez S., Becerra V.M., Llata J.R., Gonzalez-Sarabia E., Torre-Ferrero C., Perez-Oria J.	Working Together: A Review on Safe Human–robot Collaboration in Industrial Environments	2017	SAF	Not relevant - 2° round of screening	
Djuric A.M., Rickli J.L., Urbanic R.J.	A Framework for Collaborative Robot (CoBot) Integration in Advanced Manufacturing Systems	2016	SAF	Not relevant - 2° round of screening	
Conesa-Muñoz J., Valente J., Del Cerro J., Barrientos A., Ribeiro A.	A multi-robot sense-act approach to lead to a proper acting in environmental incidents	2016	SAF	Not relevant - 1° round of screening	
De Momi E., Kranendonk L., Valenti M., Enayati N., Ferrigno G.	A neural network-based approach for trajectory planning in robot-human handover tasks	2016	SAF	Not relevant - 2° round of screening	
Makris S., Karagiannis P., Koukas S., Matthaiakis A.-S.	Augmented reality system for operator support in human–robot collaborative assembly	2016	SAF	Not relevant - 2° round of screening	
Kinugawa J., Kanazawa A., Kosuge K.	B-PaDY: robot co-worker in a bumper assembly line	2016	SAF	Not relevant - 1° round of screening	
Cherubini A., Passama R., Crosnier A., Lasnier A., Fraisse P.	Collaborative manufacturing with physical human–robot interaction	2016	SAF	Relevant	SAF/ERG
Bloss R.	Collaborative robots are rapidly providing major improvements in productivity, Safety, programing ease, portability and cost while addressing many new applications	2016	SAF	Not relevant - 2° round of screening	
Hull T., Minarcin M.A.	Considerations in Collaborative Robot System Designs and Safeguarding	2016	SAF	Not relevant - 2° round of screening	
Beluško M., Hegedüš M., Fedorko G.	Creating Visual Work Instructions to Ensure Safe and Fluent Operation of the Semi-Automatic Production Lines	2016	SAF	Not relevant - 1° round of screening	
Wang Z., Yip H.M., Navarro-Alarcon D., Li P., Liu Y.-H., Sun D., Wang H., Cheung T.H.	Design of a Novel Compliant Safe Robot Joint with Multiple Working States	2016	SAF	Relevant	SAF
Hugues O., Weistroffer V., Paljic A., Fuchs P., Karim A.A., Gaudin T., Buendia A.	Determining the Important Subjective Criteria in the Perception of Human-Like Robot Movements Using Virtual Reality	2016	SAF	Relevant	ERG
Savazzi S., Rampa V., Vicentini F., Giussani M.	Device-Free Human Sensing and Localization in Collaborative Human–Robot Workspaces: A Case Study	2016	SAF	Relevant	SAF
Zhang P., Jin P., Du G., Liu X.	Ensuring Safety in human–robot coexisting environment based on two-level protection	2016	SAF	Relevant	SAF
Kim K.H., Park I.J., Choi J.-H., Rhim S.	Evaluation of head-collision Safety of a 7-DOF manipulator according to posture variation	2016	SAF	Not relevant - 2° round of screening	
Vysocky A., Novak P.	Human - Robot collaboration in industry	2016	ERG	Not relevant - 2° round of screening	
Vysocky A., Novak P.	Human - Robot collaboration in industry	2016	SAF	Double file	
Fakhruldeen H., Maheshwari P., Lenz A., Dailami F., Pipe A.G.	Human robot cooperation planner using plans embedded in objects	2016	ERG	Not relevant - 2° round of screening	

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Table 12 (*continued*)

Authors	Title	Year	Scopus last keyword	Relevance	Final classification
Dagalakis N.G., Yoo J.-M., Oeste T.	Human–robot collaboration dynamic impact testing and calibration instrument for disposable robot Safety artifacts	2016	SAF	Relevant	SAF
Tsarouchi P., Makris S., Chryssolouris G.	Human–robot interaction review and challenges on task planning and programming	2016	SAF	Not relevant - 2° round of screening	
Luo R.C., Kuo C.-W.	Intelligent seven-DoF robot with dynamic obstacle avoidance and 3-D object recognition for industrial cyber-physical systems in manufacturing automation	2016	SAF	Not relevant - 2° round of screening	
Labrecque P.D., Hache J.-M., Abdallah M., Gosselin C.	Low-Impedance Physical Human–Robot Interaction Using an Active-Passive Dynamics Decoupling	2016	SAF	Relevant	SAF
Rengevic A., Kumicakova D.	New possibilities of robot arm motion simulation	2016	SAF	Relevant	SAF
Shackleford W., Cheok G., Hong T., Saidi K., Shneier M.	Performance Evaluation of Human Detection Systems for Robot Safety	2016	SAF	Relevant	SAF
Cheng P.-J., Ting H.-Y., Huang H.-P.	Safe Human Robot Interaction using Model Matching Control	2016	SAF	Not relevant - 2° round of screening	
Zanchettin A.M., Ceriani N.M., Rocco P., Ding H., Matthias B.	Safety in Human–Robot Collaborative Manufacturing Environments: Metrics and Control	2016	SAF	Not relevant - 2° round of screening	
Lee S.-D., Song J.-B.	Sensorless collision detection based on friction model for a robot manipulator	2016	SAF	Relevant	SAF
Scholer M., Vette M., Rainer M.	A lightweight Robot System Designed for the optimisation of an automotive end-off line process station	2015	ERG	Relevant	SAF
Scholer M., Vette M., Rainer M.	A lightweight Robot System Designed for the optimisation of an automotive end-off line process station	2015	SAF	Double file	
Mitka E., Mouroutsos S.G.	Applying the STAMP system Safety engineering methodology to the design of a domestic robot	2015	SAF	Not relevant - 1° round of screening	
Marvel J.A., Falco J., Marstio I.	Characterizing task-based human–robot collaboration Safety in manufacturing	2015	SAF	Relevant	SAF
Wang L.	Collaborative robot monitoring and control for enhanced sustainability	2015	SAF	Relevant	SAF
Chen F., Zhong Q., Cannella F., Sekiyama K., Fukuda T.	Hand gesture modeling and recognition for human and robot interactive assembly using hidden markov models	2015	SAF	Relevant	SAF
Faber M., Bützler J., Schlick C.M.	Human–robot Cooperation in Future Production Systems: Analysis of Requirements for Designing an Ergonomic Work System	2015	ERG	Not relevant - 2° round of screening	
Faber M., Bützler J., Schlick C.M.	Human–robot Cooperation in Future Production Systems: Analysis of Requirements for Designing an Ergonomic Work System	2015	SAF	Double file	
Marcan P., Rofár J., Micieta B.	Implementation of robots cooperating with humans in production systems	2015	SAF	Relevant	SAF
Massa D., Callegari M., Cristalli C.	Manual guidance for industrial robot programming	2015	SAF	Not relevant - 2° round of screening	
Ibarguren A., Maurtua I., Pérez M.A., Sierra B.	Multiple target tracking based on particle filtering for Safety in industrial robotic cells	2015	SAF	Relevant	SAF
Ceriani N.M., Zanchettin A.M., Rocco P., Stolt A., Robertsson A.	Reactive Task Adaptation Based on Hierarchical Constraints Classification for Safe Industrial Robots	2015	SAF	Relevant	SAF
Medina J.R., Lorenz T., Hirche S.	Synthesizing anticipatory haptic assistance considering human behavior uncertainty	2015	SAF	Relevant	ERG
Pransky J.	The Pransky interview: Dr Esben Ostergaard, inventor, co-founder and CTO of Universal Robots	2015	SAF	Not relevant - 2° round of screening	
Crowther P.	YuMi®: Introducing the world's first truly collaborative dual-arm robot that will radically change assembly lines	2015	SAF	Not relevant - 2° round of screening	
Charalambous G., Fletcher S., Webb P.	Identifying the key organisational human factors for introducing human–robot collaboration in industry: an exploratory study	2015	ERG	Relevant	ERG

and psychophysical aspects of collaboration. These innovations should allow the implementation of safe, ergonomic, trustworthy and efficient collaborative production systems.

Appendices

Appendix – Step 4: papers processing and classification.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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