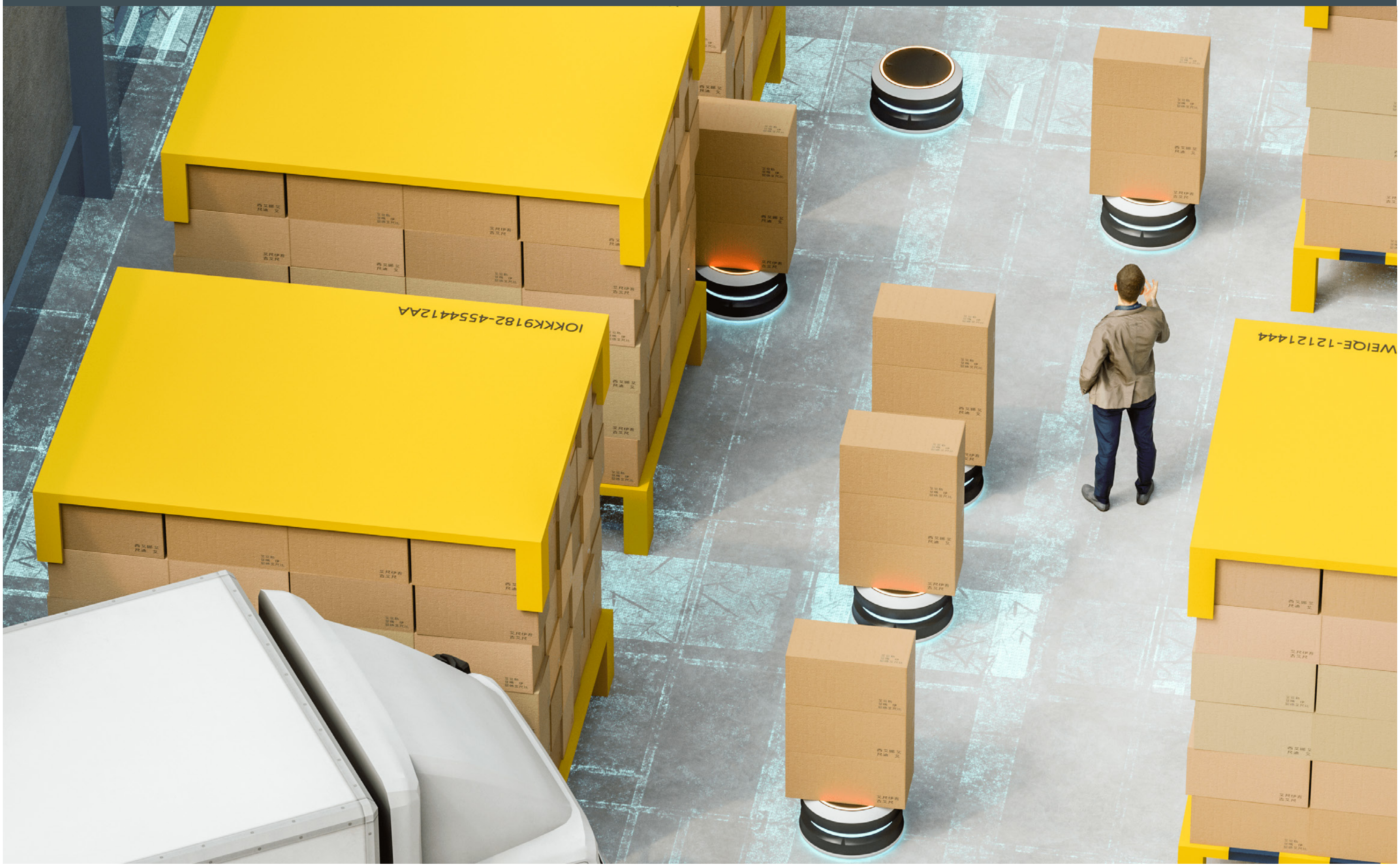
Principles to support safe design of collabortive robotic systems



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Prepared by:

Matthias Guertler[1] (chief investigator)

Manisha Amin[2]

Jane Cockburn[3]

Marc Carmichael[1]

Leila Frijat[2]

Rebecca Grace[2]

Victor Hernandez Moreno[1]

Sazzad Hussain[4]

Gavin Paul[1]

Nathalie Sick[1]

Laura Tomidei[1]

Annika Wambsganss[1]

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[1] University of Technology Sydney, Ultimo NSW 2007

[2] Centre for Inclusive Design, Ultimo NSW 2007

[3] Kairos Now, Manly NSW 2095

[4] Centre for Work Health and Safety, NSW Department of Customer Service, Sydney NSW 2000

Executive summary

Background

With the development of collaborative robots, a fundamental paradigm shift in robotics and human-robot interaction has emerged in the workplace. While traditional industrial robots are unaware of their environment and must be strictly separated from human operators to guarantee their safety, modern robotic systems are now capable of safely interacting with humans in shared workspaces. They offer a myriad of previously unimaginable applications, but also can create new working environments potentially raising work, health, and safety concerns. This project aims to develop guidelines for the safe adoption and use of collaborative robots (cobots) in the workplace, and to do so, it is crucial to understand the existing safety measures that can mitigate the potential work, health, and safety risks associated with working with cobots. While the report on "Work health and safety risks and harms of cobots" identified the potential risks and harms associated with working with cobots, this research focuses on mitigation strategies and design principles for collaborative human-robot workspaces.

Method

Given this project's socio-technical and exploratory nature, a mixed-method approach was applied involving a structured literature review and an interview study. The structured literature review incorporates international standards, academic literature, and industry outlets, which provide a systematic overview and insights into the current state of the art of principles to support safe design of collaborative robotic systems in academia and industrial practice around the globe. Design-led methods include semi-structured interviews with stakeholders across the cobot industry including but not limited to: cobot manufacturers, distributors, suppliers, system integrators, industry partners, and cobot users, as well as interested/potential cobot users in industry. The interview study evaluates and humanises the literature review findings against the experiences of these stakeholders and identify emerging themes and gaps not addressed in existing literature or standards. Furthermore, it investigates the differing safety practices and risk mitigation strategies that occur across various industries and work settings and explores stakeholders' attitudes and behaviours towards safe cobot practices.

Discussion

The findings of the literature review and the interview study revealed a taxonomy of risk mitigation and safety strategies related to human cobot collaboration. In line with the findings of "Work health and safety risks and harms of cobots", the standards maintain a focus on physical risks and respective mitigation strategies. While safety measures targeting physical and ethical risks were well-addressed by the literature and the interview study respectively; psychological risks were not as strongly considered. The engagement of a variety of stakeholders across the cobot industry was crucial in addressing the complexity of safe cobot implementation as a socio-technical system. This enabled the study to explore the human factors that contribute to risk mitigation and safety strategies and determined gaps in current resources in addressing the complexity of human-cobot blended workplaces. The taxonomy was synthesised into five design principles for safe human-robot collaboration that will inform the development of cobot safety guidelines.

1. *Understanding cobot and safety features* includes an understanding of what your cobot can and cannot do in terms of tasks, behaviour and safety features as well as an understanding of how your cobot system ensures safety and how activities might trigger unwanted safety features.
2. *Ensuring a human focus* includes considering different cobot experience levels of operators and 'temporary workplace visitors' as well as involving your staff in the cobot workplace design to maximise the benefits for them and provide upskilling and social contacts.
3. *Aligning cobot, workspace and workflow* includes building an understanding that the cobot is only one part of a socio-technical cobot system and, as a result, treating cobot, end-effector tools, workplace and workflow processes as an interconnected system, which needs to be aligned to ensure safety ("cobot readiness" of all parts).
4. *Ensuring security and protection* includes preventing and identifying unallowed tempering with cobot hardware and software as well as looking out for potential issues and consequences of tampering on the cobot, human, end-effector tools, workplace and workflow processes.
5. *Supporting ease of use* includes ensuring the cobot and its safety features are user friendly and support the staff's work and that the positive and negative impact of engaging with the cobot is considered.

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Introduction

Due to industry trends such as the shift from mass production to mass customisation, the collaboration between human operators and robotic assistive systems has become more and more attractive. The recent development of a new type of robotic system capable of human-robot collaboration (cobots) opens up possibilities and advantages in deploying robots in industrial environments and workplaces. Even though such physical robotic assistance promises many advantages on the factory floor, including low-cost automation and flexibility in small-batch production, the fusion of the humans' and robots' workspaces entails a variety of risks to operators. Considering the complex socio-technical nature of this system, the safety of the operator is exposed to potential physical, psychological and ethical risks. For this reason, international standards specify protective measures for robots, robotic systems, sensing devices, industrial tooling components, and their integration. Despite the formal coverage in standards, the current strategies to ensure cobot safety appear to be limited to largely mitigating physical harm and working environments that produce industrial and manufacturing goods. As cobots continue to expand into new industries such as medicine and media, there is a growing need for these standards to be adapted so that safe human-robot collaboration can be addressed in a wider array of work environments, cobot applications, and organisations that will use cobots (cobot users in the following).

Recent scientific literature of human-robot collaboration reveals an increasing interest in intelligence-enhanced systems, improved cost-effectiveness, and social science aspects. The latter is particularly emphasising the safety of such systems, indicating an increased importance to consider a collaborative human-robot workstation as a complex socio-technical system in which the human operator is potentially exposed to physiological and ethical risks.

In order to define comprehensive safety guidelines for the use of collaborative robots it is important to understand the gaps between existing cobot risks and safety measures. Based on the risks identified earlier in this project (Centre for Work Health and Safety NSW et al., 2021), this phase of research addresses the following objectives:

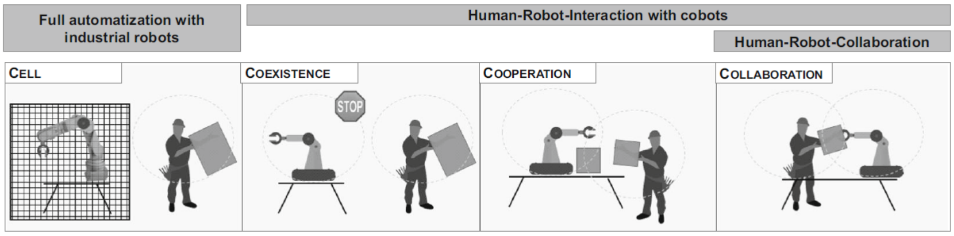
1. Investigation of existing risk mitigation and safety strategies in a human-robot collaboration environment.
2. Identification of design principles to support safe human-robot collaboration.

For this purpose, a systematic review of academic and grey literature was conducted to investigate existing risk mitigation and safety strategies related to the use of collaborative robots in the workplace. Subsequently, an interview study took place to confirm and expand upon the risk mitigation and safety strategies identified in the literature review.

The findings of the literature review and the interview study revealed a taxonomy of risk mitigation and safety strategies related to human cobot collaboration. The taxonomy was synthesised into design principles for safe human-robot collaboration. Furthermore, the study explored the human factors that contribute to risk mitigation and safety strategies, and determined potential gaps in addressing the variety of cobot-specific risks.

Background

To set the scene for human robot collaboration, a robot is considered collaborative when (a) it shares the workspace with a human, (b) tasks are performed at the same time and potentially require physical contact with a human, and (c) its implementation include dimensions specified by the respective standards (ISO 15066:2016, ISO10218-2:2011) (see Figure 1) (Centre for Work Health and Safety NSW et al., 2021).



Working steps	Sequential			Simultaneously
Working space	Separated working spaces		Shared collaboration space If synchronised: Timely separated	
Working tasks	Tasks are not linked		Linked tasks	Shared tasks
Physical contact	Impossible		Possible, not necessary	Possible, often desired
Minimal safety requirements according to DIN EN ISO 10218-1	Automatic operation with safeguards	Safety-rated monitored stop	Speed and separation monitoring Power and force limiting	Hand-guided control
Robot speed	Maximum speed	Limited speed		

Figure 1: Interaction types and characteristics of robots *(Kopp et al., 2020)*

Due to the socio-technical nature of these systems, there are four dimensions that need to be considered during their implementation, namely (1) human operator, (2) cobot, (3) working system, and (4) enterprise and contextual (see Figure 2). Not only the human operator and the cobot need to be taken into account individually, but also the working system or the cell design of the collaborative space where human and robot interact. In addition, enterprise and contextual factors play a role, such as task processes, roles or responsibilities, and workforce training (Kopp et al., 2020). Accordingly, the risks and safety aspects extend across these dimensions.

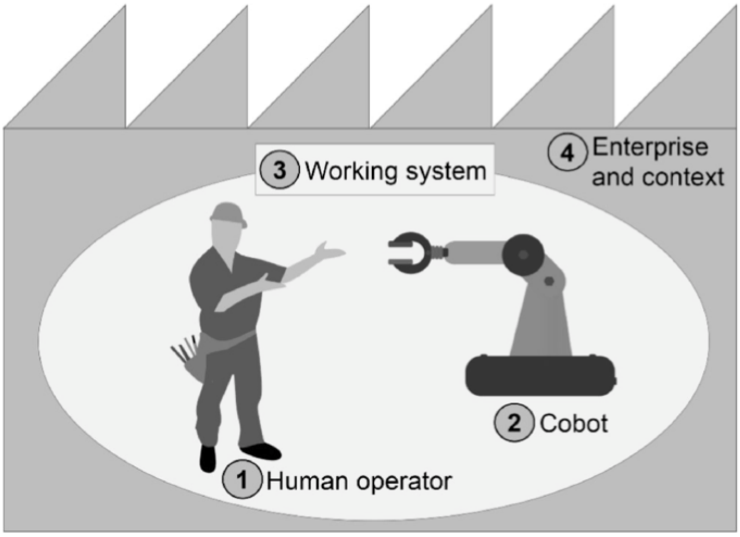


Figure 2: Dimensions of human-robot collaboration *(Kopp et al., 2020)*

Previous research in this project has revealed that in practice there is often confusion between robots and cobots, which can generate additional risks for the human operator (Centre for Work Health and Safety NSW et al., 2021). In some instances, industrial robots are converted for collaborative uses without using the appropriate measures, leading to additional risks. Three main categories have been identified in phase 2 based on the type of harm that the risks can have on workers: physical, psychological and ethical risks (see Table 1). The majority cover physical risks, comprising hazardous collisions, cybersecurity, lack of focus, loss of movement control, debris and pinch points. With the increasing proliferation of cobots, psychological and ethical aspects are gaining increasing concerns. Psychological risks include mental strain, lack of trust and complicated interaction mechanisms; while ethical risks refer to social environment, social impact, social acceptance and data collection. However, there appears to be little consideration for the psychological harm that could be caused by working with cobots. For example, anxiety and stress within workers can be caused not only by their work conditions in close proximity to robots but also by job precarity and fear for losing their role (Centre for Work Health and Safety NSW et al., 2021).

International standards provide a variety of protective measures as a prerequisite for the implementation of safe human-robot collaboration. Generally, safety standards are grouped in three categories (see Table 2 for the full list of safety standards). *Type A* defines the terminology and methodologies used in safety of machinery; *Type B* refers to specific safety aspects for general machinery types and *Type C* refers to safety countermeasures for specific machines. If *Type C* standards are provided for a specific machine, these have the priority over *Type A* and *Type B*. The relevant *Type C* standard specific to collaborative robots is ISO/TS

15066:2016 (BSI Standards Publication, 2016), and is considered supplemental to the standards for industrial robots ISO 10218-1/2:2011 (BSI Group, 2011a, 2011b).

Table 1: Summary of risks and harms related to human-robot collaboration

Harm	Risk	Description
Physical	*Hazardous collisions*	As robot and operator share the same space, non-functional or unwanted contacts may occur.
	Cybersecurity	Cyber-attacks may cause robots to move unpredictably and harm the operator.
	Lack of focus	When the operator lacks concentration and focus, tasks may not be fulfilled as intended and cause mishandling of the cobot, which can lead to physical harm.
	Loss of movement control	The loss of movement control of a cobot system is a risk potentially causing physical damage to the operator.
	Debris	Debris created by a cobot during task operation.
	Pinch points	A point where humans and/or other materials and objects can be caught between moving and/or stationary parts of a cobot.
Psychological	*Mental strain*	Collaborative settings may cause stress and could negatively affect the psychological state and mental strain of humans.
	Lack of trust	The lack of trust from the worker towards the cobot hinders safety and the development of a sense of comfort.
	Complicated interaction mechanisms	Complicated information exchange between human and robot can cause psychological harm, e.g. in form of stress or extra-work to humans.
Ethical	*Social environment*	As opposed to regular settings in which operators interact socially during work, collaborative robots can negatively affect the harmony of the social environment.
	Social impact	Introducing cobots may change the role of some workers and induce a general fear of job loss.
	Social acceptance	Communities in which cobots are introduced have varying forms of predisposition for such a technology.
	Data collection	Operators and user data may be collected, used, and sold without user consent.

Table 2: Safety standards

Standards	HRC Relevance	Type
ISO 12100, IEC 61508	Terminology and methodology used in safety of machinery (i.e. risk assessment and risk reduction, functional safety of electrical, electronic and programmable electronic equipment)	A
ISO 13849-1, IEC 62061	Specific safety aspects: design of low complexity safety system and "Safety PLCs"	B1
ISO 13850, ISO 13851	Safety aspects for safeguarding: specific functional aspects of emergency-stop devices and two-hand control devices	B2
ISO 10218-1	Safety requirements for robot manufacturers	C
ISO 10218-2	Safety requirements for system integrators	C
ISO 15066	Additional information and guidance for collaborative robots	C

At present, ISO/TS 15066:2016 represents the only standard specifying safety measures and design principles for the use of cobots (BSI Standards Publication, 2016). It defines protective measures unique to the implementation of and work with collaborative robots. These measures include three fundamental aspects, each specified in a separated clause (see Figure 3).

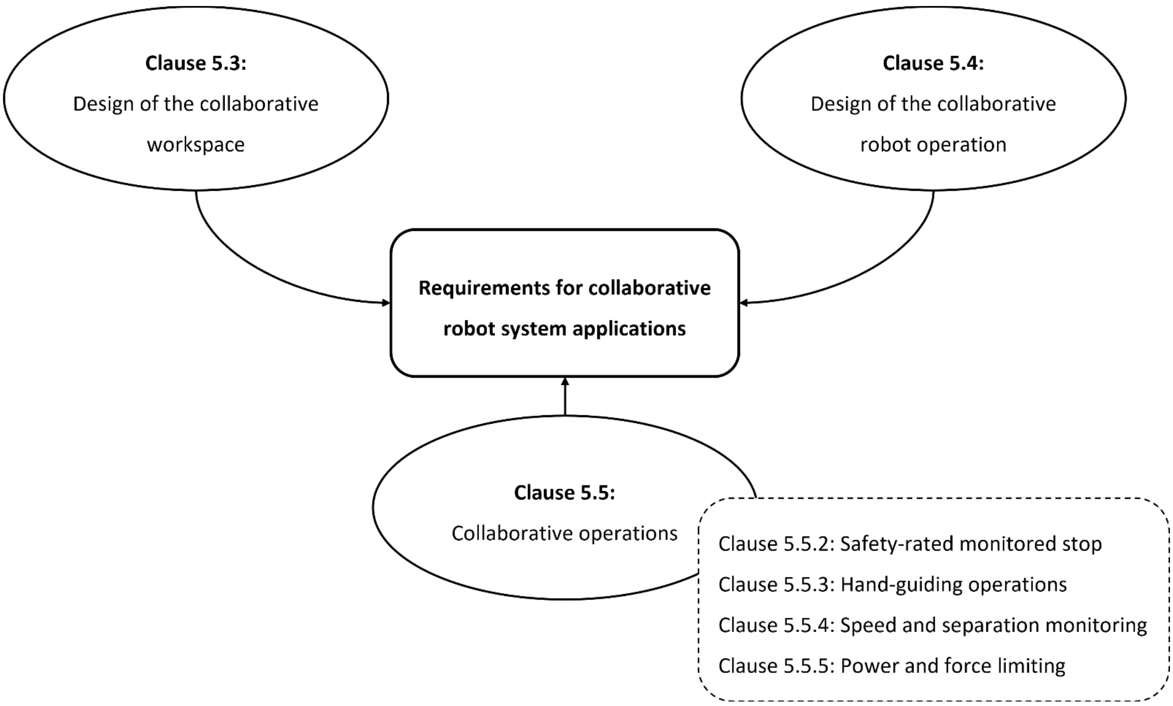


Figure 3: Protective measures according to ISO/TS 15066

Safety assuring requirements for the design of the collaborative workspace are defined in clause 5.3. While guaranteeing the possibility of performing all intended tasks, a comprehensive risk assessment shall mitigate any risk introduced by the presence and location of additional machinery or equipment. As a protective measure, safety-rated soft axis and space limiting defined in ISO 10218-1:2011 5.12.3 should be applied to reduce the restricted space wherever reasonable. When designing the collaborative workspace, any risk associated with whole-body trapping or crushing between the robot system and other structures must be eliminated or safely controlled.

Clause 5.4 discusses the design of the collaborative robot operation. Any operator working with the collaborative robot shall be capable of either stopping robot motion at any time by a single action or having an unobstructed means of exiting the collaborative workspace. The former can be assured through an enabling device, emergency stop device or by hand, in the case of robots that include this feature. Collaborative robots that provide inherently safe design measures or active safety-rated limiting functions do not require the use of an enabling device. In this case, safety-rated limiting functions must always remain active, and the limits shall be set to a level that provides sufficient risk reduction. Information on active settings and collaborative safety parameters configuration must be protected against unauthorised and unintentional changes. In the occurrence of a detected failure in safety-related parts, the operation shall not resume until reset by a deliberate restart action with the operator outside of the collaborative workspace. Finally, awareness is awakened for the critical part of transitioning between non-collaborative and collaborative operations. The implementation of a visual indicator to identify the transition is mentioned as a potential measure.

ISO/TS 15066 clause 5.5 comprehensively revises the definition of the four acceptable modes for collaborative operations introduced in the preliminary ISO 10218-1/2:2011 standards. These build the essence of working with collaborative robots and include “safety-rated monitored stop (SMS)”, “hand-guiding operation (HG)”, “speed and separation monitoring (SSM)”, and “power and force limiting (PFL)” (see Figure 4).

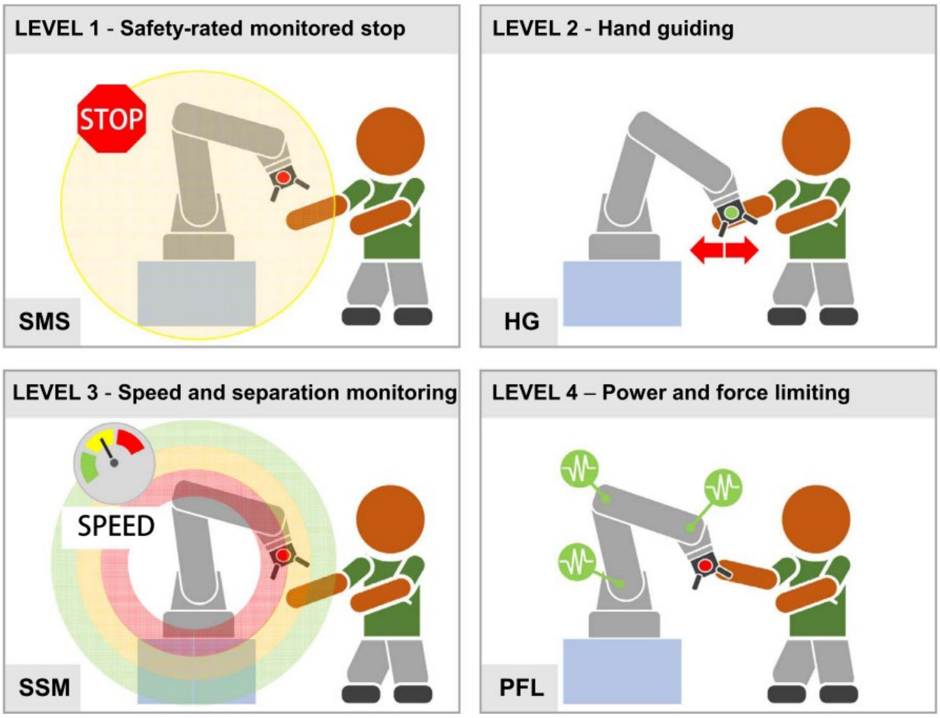


Figure 4: Collaborative operation modes (Villani, Pini, et al., 2018)

In summary, the majority of existing safety measures and design principles predominantly target the mitigation of physical risks, while ethical and psychological risks are covered to a much lesser extent. However, the implementation of human-robot collaboration requires the workspace to be set up as a multifaceted socio-technical system. Compared to other machines considered autonomous, such a system requires more than a performance-oriented selection of a cobot. To safely design human-robot collaboration, the operator's physical, ethical and psychological safety is of paramount importance. Hence, to gain a comprehensive understanding of how physical, ethical and psychological risks can be mitigated, it is necessary to go beyond standards to systematically identify and categorise existing safety measures. This research suggests a systematic literature review to capture the state-of-the-art in cobots risk mitigation and safety strategies, enriched by expert interviews to add current industrial practice and a human-centred perspective. This allows to map risks and existing safety measures in order to identify gaps and focus areas for developing cobot safety guidelines.

Method

This section presents the methods applied to the structured literature review and the interview study.

Structured literature review

The structured review includes academic and grey literature, covering cobot-specific as well as interdisciplinary literature to identify design principles for safe human-cobot workplaces. This includes human-machine interaction and systems engineering principles around a socio-technical system perspective.

Academic literature

The systematic review of academic literature is conducted by adopting a systematic approach to analyse existing research in the field (see Figure 5). The method used to define the collection of relevant documents informing the analysis follows established research practices (Denyer & Tranfield, 2009). Based on the research aims and scope, strategies and principles that support safe design in human-robot collaboration are incorporated based on relevant terms associated with risk mitigation, safety assurance and design principles. The composite search query developed for the systematic analysis is defined as follows:

TITLE-ABS-KEY (human AND robot AND collaborat AND ((risk W/2 (mitigat* OR reduc*)) OR (safe* W/2 (assur* OR ensur* OR guarant*)) OR (design* W/2 (proper* OR crit* OR consider* OR safe* OR principle OR guideline))))*

The Scopus database was used as it provides high-quality scholarly literature, including documents from a range of scientific fields. The search in October 2021 returned 458 results. This pool of documents was analysed using quantitative analysis. As research publication relevance and reputation are mainly measured by citations, search results are refined using the average annual citation number. For this report, documents that show a value of 5.0 average annual citations or above are included, leading to a sample of 42 documents. To further refine the sample for the qualitative analysis, the publications are examined in detail based on the following inclusion criteria:

1. The document addresses design measures to support safety in human-robot collaboration.
2. The document illustrates approaches to mitigate risks for human-robot collaboration in a socio-technical system.
3. The document focuses on collaborative robots in an industrial environment (use case) or it discusses design principles that can be transferred to the cobot use case.

Although this report aims to identify techniques and design principles for industrial settings, it does not exclude other fields of application, such as service, space or medical robotics. Moreover, the deliberate integration of interdisciplinary literature seeks to provide a comprehensive analysis of all supportive measures.

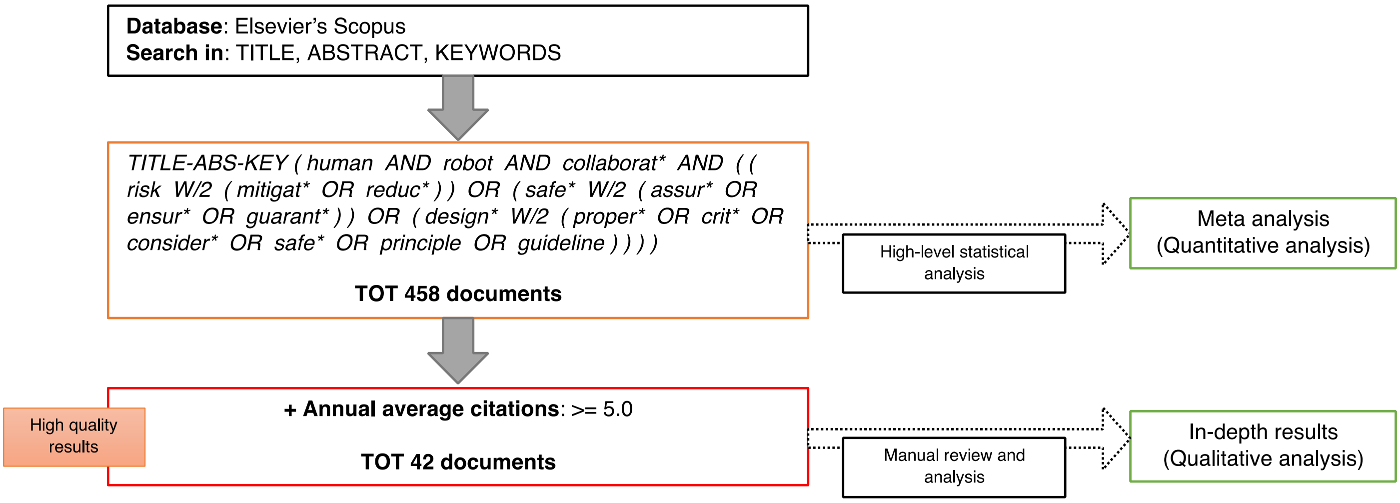


Figure 5: Methodology of the systematic literature review

Grey literature

In addition to the systematic review of academic literature, grey literature has been analysed to find relevant documents that discuss established best practices, incorporated strategies and principles for safe design in human-robot collaborations. This search was conducted using the advanced search option of the Google search engine, by searching for grey literature including the previously identified keywords:

("human robot collaboration" AND ("risk mitigation" OR "risk reduction" OR "safety guideline" OR "safety principle")

The search was conducted in November 2021. Additionally, a snowball system was applied, which is a method of forward and backward literature search based on citations and linkages (Kornmeier, 2007).

The advanced search for the above-mentioned keyword combination returned a total of 4,920 results. In the first step, academic literature published on Sagepub, Sciencedirect or Researchgate were excluded, as they had already been covered in the academic literature section. Additionally, articles published on YouTube, standards, and articles in other languages than English or German were excluded. The remaining 435 search results were selected according to their type, publishing company and general relevance for the underlying topic. The most relevant results were then shortlisted (n=43), to which the inclusion criteria, identified in the academic literature section, were applied. Finally, a total of 23 documents have been analysed for identifying risk mitigation strategies for human-robot collaboration (see Figure 6).

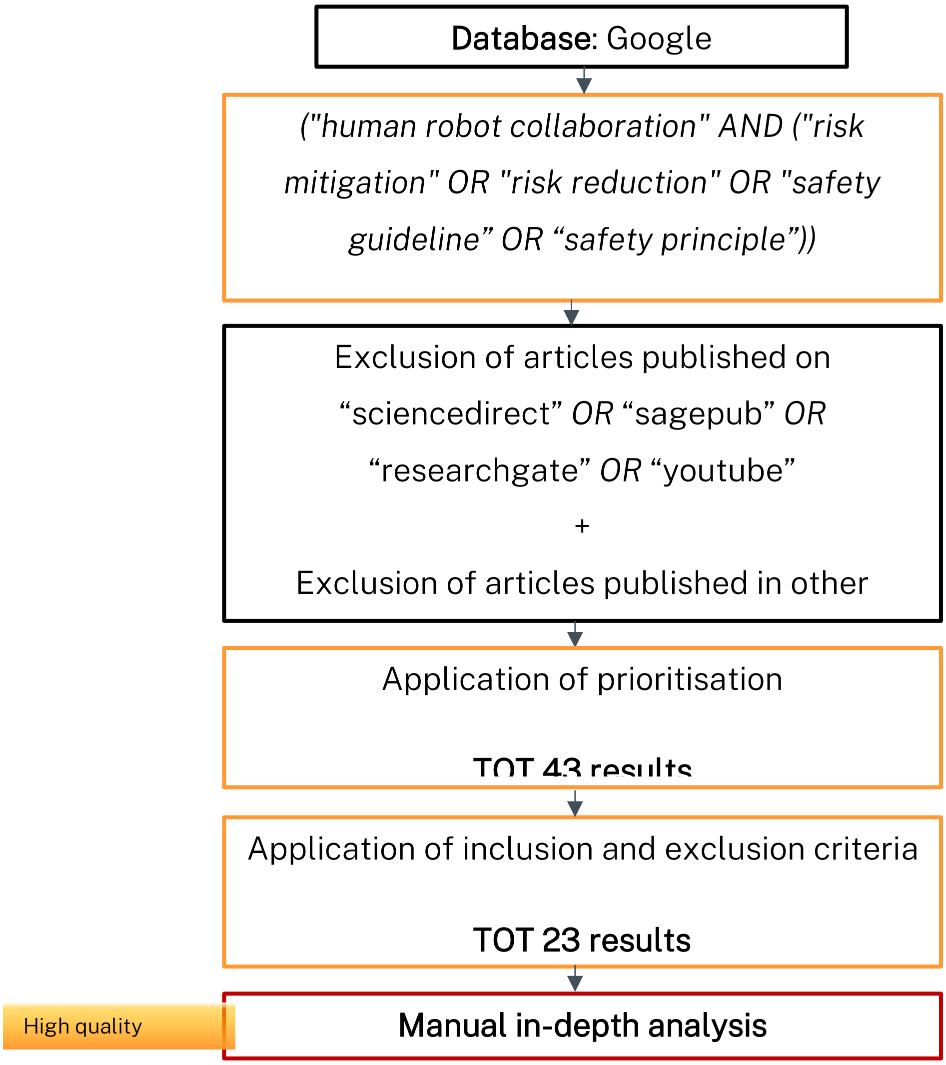


Figure 6: Methodology of the grey literature analysis

Interview study

The interview study employed the contextual enquiry methodology to conduct interviews. The study explored the human attitudes and perceptions of various stakeholders across the cobot industry to understand how safe design can be supported and enabled. Furthermore, it had built upon the literature review to develop a holistic understanding of the existing safe work and risk mitigation practices that are employed by various stakeholders within the industry. The purpose of this study was to:

1. Assess and expand the literature review's identification of risk mitigation strategies as they pertain to human-robot collaboration.

2. Identify potential gaps and emerging themes that are not addressed in the literature review or existing standards and guidelines.
3. Investigate the differing safety practices with cobots across a variety of industries and work settings.
4. Understand the attitudes and perceptions of cobot industry stakeholders that contribute to safe design.

Recruitment strategy

The interview study employed a combination of purposive sampling and snowball recruitment strategies, to capture a wide array of perspectives on safe human-robot collaboration. The intentionally broad inclusion criteria (see Table 3) ensured that the study included a diverse cross-section of participants, use-cases and industry sectors. Considering the unclear definition and use-cases between collaborative and industrial robots, the recruitment did not exclude research participants that had experience working with industrial robots. This inclusion was especially important to recruit participants from non-traditional cobot users' organisations who do not have robotic, manufacturing, or engineering backgrounds and may not understand the nuanced differentiations between different robot types.

Table 3: Inclusion and exclusion criteria for the interview study

Inclusion criteria	Exclusion criteria
• *Individuals who have past or present experience working with cobots or robots.* • *People who possess knowledge about the potential safety measures that can be adopted.* • *Organisations considering utilising human-robot collaborative applications*	• *Individuals who do not interact with cobots or specifically address risks, safety measures or risk assessment tools.* • *Individuals or organisations that do not work with cobots/robots and have no future interest in adoption.*

Initially, 70 individuals and organisations were identified as appropriate research participants and engaged via phone calls and/or participation email requests. In total there were 19 interviews conducted with 22 people who participated in a one-hour, semi-structured, online interview. From this group, three of the interviews were group interviews consisting of two participants who belonged to the same organisation.

During the recruitment process, research participants were asked to self-identify their interaction with the cobot industry using the following categories (see Table 4): manufacturer, distributor, supplier, integrator, cobot user organisations, potential cobot user organisations, industry partner, and other. Table 5 presents the breakdown of the participants according to sector and occupation. 11 of the participants were engaged via recommendation from the research team and other research participants. It should be noted that this is inclusive of the participants recruited for the first stage of the research project.

Table 4: Research participant categories and definitions

Sector	Description
Manufacturers	Companies that are responsible for the design and manufacturing of the physical cobot.
Distributors	Companies that are authorised by manufacturers to stock and provide some implementation support for specific cobot brands.
Suppliers	Companies that sell cobots and provide implementation support.
Integrators	Companies that assist users in integrating cobots into workplaces and configuring software and hardware systems.
Cobot users	Companies or individuals that use cobots in their operations.
Potential cobot users	Companies or individuals interested in purchasing and using cobots.
Industry partners	Individuals who are associated in the development of cobot industry, including academic researchers and 3rd party risk assessors

Table 5: Breakdown of research participants

No#	Interview type and purpose	Interview participant category	Industry/sector	Participant position title
1	Individual – WP3	Cobot User	Tertiary Education	Coordinator/ Technician
2	Individual – WP3	Potential Cobot User	Food	Operational Manager
3	Group (1 of 2) – WP3	Distributor, Supplier, Integrator	Robotics/ Automation	Electronic Engineer
3	Group (2 of 2)– WP3	Distributor, Supplier, Integrator	Robotics / Automation	Founder & Project Manager
4	Group (1 of 2) – WP3	Industry Partner (*Risk Assessor*)	Independent Product Safety Assessors	Director

4	Group (2 of 2)– WP3	Industry Partner (Risk Assessor)	Independent Product Safety Assessors	Business Development Manager
5	Individual – WP3	Cobot User	Film	Director of Photography & Senior Motion Control Operator
6	Individual – WP3	Manufacturer	Safety Peripheral Equipment	Chief Technology Officer
7	Individual – WP3	Industry Partner (Risk Assessor)	Work, Health, and Safety	Work Health and Safety Inspector
8	Individual – WP2 + 3	Industry Partner (Researcher)	Robotics	Professor
9	Individual – WP2 + 3	Industry Partner (Researcher)	Robotics	Senior Lecturer
10	Individual – WP2 + 3	Supplier	Robotics/ Automation	Business Development Manager
11	Individual – WP2 + 3	Integrator	Robotics/ Automation	Director
12	Individual – WP2 + 3	Integrator + Cobot User	Higher Education	CEO
13	Individual – WP2 + 3	Supplier + Integrator	Robotics/ Automation	Project Engineer
14	Individual – WP2 + 3	Cobot User	Physical Rehabilitation	CEO & Founder
15	Individual – WP2 + 3	Cobot User	Custom Manufacturing	Operator and Head of Finishing
16	Individual – WP2 + 3	Industry Partner (Researcher)	Advanced Manufacturing	Professor & Centre Director
17	Individual – WP2 + 3	Cobot User	Higher Education	Technical Officer
18	Individual – WP2 + 3	Cobot User	Custom Manufacturing	Operational Manager
19	Group (1 of 2) – WP2 + 3	Supplier	Cobot Manufacturer	Operational Manager
19	Group (2 of 2) – WP2 + 3	Supplier	Cobot Manufacturer	Sales Engineer

Interview procedure

The semi-structured, one-hour interviews were conducted online using ‘Microsoft Teams’, guided by a set of sample interview questions (Appendix A). The interviews commenced on the 19th of August 2021, with ethics approval (UTS HREC REF NO. ETH21-6244). Research participants were briefed on the purpose of the interview and verbal consent prior to the formal interview and for recording for note-taking purposes. Verbal consent was deemed adequate given that the research project carried a low level of risk for research participants. Interview responses referenced in this report have been lightly edited for concision and readability.

The interview questions were developed to explore how research participants address the risks and harms identified in the phase 2 report (Centre for Work Health and Safety NSW et al., 2021). They also enable to reassess the findings of the literature review through the lens of research participants and identify gaps in existing standards, literature, and resources to support safe work practices. In speaking with research participants for this project's phase 2 report (Centre for Work Health and Safety NSW et al., 2021), it became clear that when participants addressed the risks or harms of cobots, they naturally shared the risk mitigation strategies that could be employed to prevent them from occurring. Therefore, the research team also utilised research findings from the previous phase to supplement these findings.

Synthesis

The recorded interviews were uploaded to the online transcription and coding platform 'Condens'. Two members of the project team were tasked with reading and coding the transcription according to the risk categories, risk mitigation strategies, and the socio-technical dimensions of design as identified by the literature review in this report and in the first milestone report. New tags were created when the research team identified gaps in the existing tag categories and literature review to highlight emerging patterns and themes. The tag categories included; cobot definition, corporate environment, equipment selection, ethical, guideline recommendations, physical, process, psychosocial/ergonomic, role and responsibilities, task assignment, training, and workspace design.

Methodological limitations

It was observed that the differences between cobots and robots seemed largely insignificant to participants, especially among users. This indicates that the recruitment may have excluded potential research participants who are working with robots collaboratively but are unaware of terms such as "cobots" or "human-robot collaboration". This is especially the case for users who work in non-industrial, manufacturing, or robotics contexts. The exclusion of unconventional use-cases for cobots or human-robot collaborative practices limits this report's recommendations for these users and for the future of the industry.

Findings

Quantitative analysis: literature review

The following sections provide early insights around research interest in risk mitigation strategies for human robot collaboration. The development of publications over time is documented in Figure 7. There is a clear trend of increasing interest in publications dealing with mitigation strategies and design principles for safe human-robot collaboration. Especially since 2014, the number of publications has steadily increased from 6 to over 85 per year in 2020. Interestingly, this trend was not interrupted by releasing the supplementary ISO/TS 15066 standard in 2016, specifically designed to define safety requirements for collaborative robots.

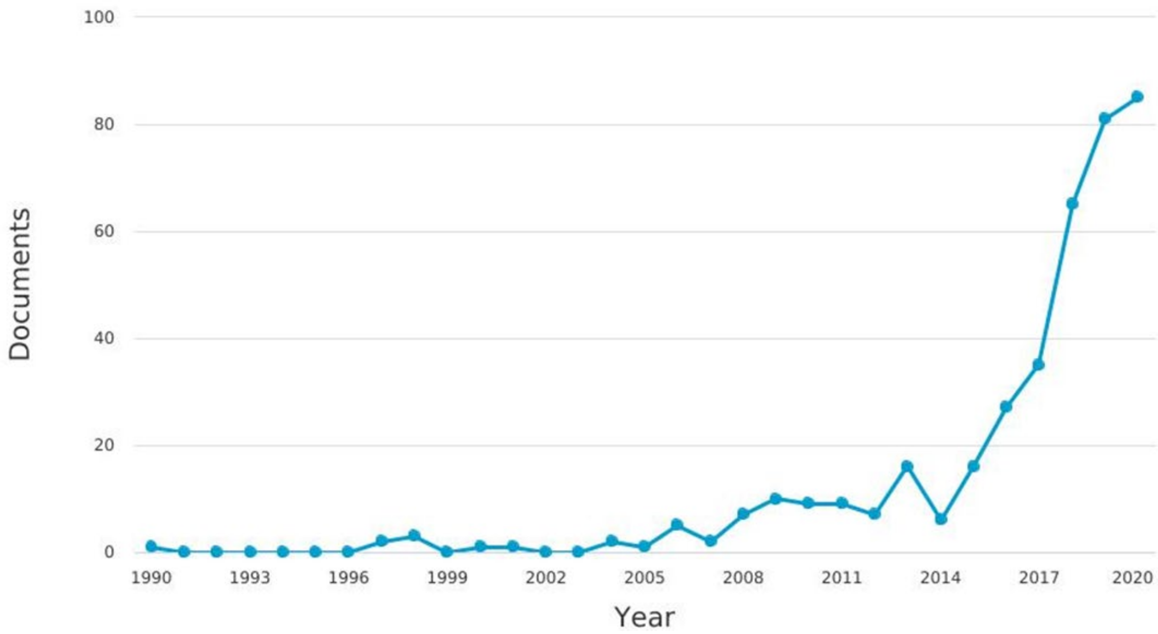


Figure 7: Development of publications in design principles for safe human-robot collaboration returned by the Scopus search over time (2021 excluded)

Figure 8 provides an overview of the development of the Google search results. Due to the limitations of Google search, the results are not limited to grey literature but include all kinds of search results being displayed for the keyword combination *"human robot collaboration" AND "safety"*. The first year of collection, 2000, shows only two results, while over the last decade, between 2010 and 2020, an exponential growth can be observed, with 5,640 results in 2020, similar to the development of relevant academic literature (see Figure 5).

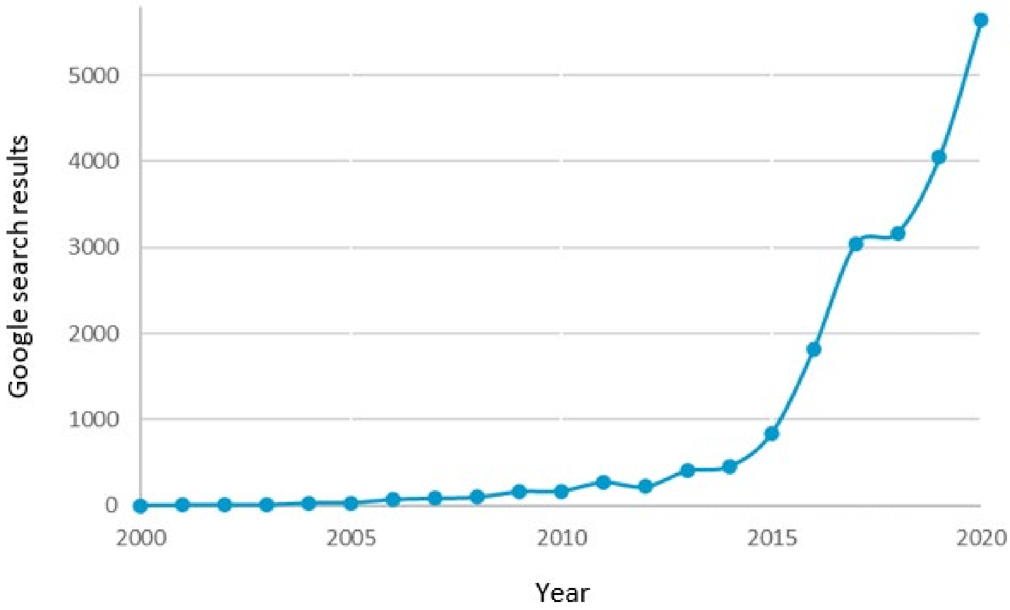


Figure 8: Development of Google search results over time (2021 excluded)

Academic contributions come from a variety of subject areas, highlighting the interdisciplinary nature of cobot research and application (see Figure 9). The subject areas Engineering, Computer Science and Mathematics dominate with a share of 36.5%, 34.7% and 11.4% of the total contributions, respectively. However, the remaining 17.4% of the documents are assigned to alternative disciplines suggesting an interdisciplinary interest in cobot safety. Interestingly, Social Science ranks fourth with 2.7%, which reveals a tendency towards a socio-technical way of thinking about human-robot collaborative workplaces.

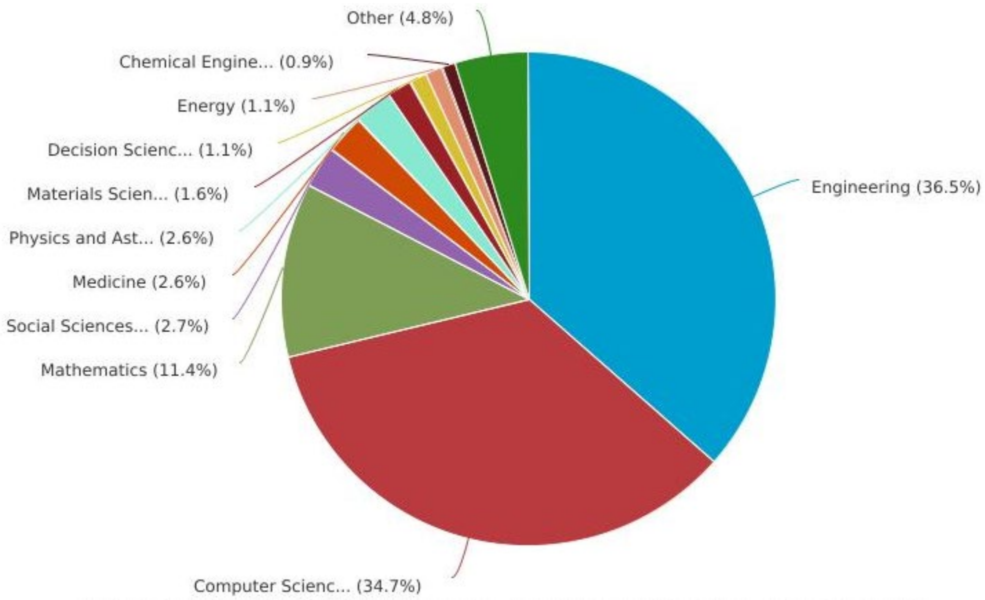


Figure 9: Subject areas contributing to the search outcome

Although contributing to a small number of publications, the evolution over time of academic publications within social sciences is notable. Similar to the overall development of publications, the number of publications in social sciences has spiked since 2018. It supports the possibility that the complexity and importance of collaborative robots goes beyond engineering concerns, suggesting an increasing requirement for social aspects to be included in safety principles for collaborative robots.

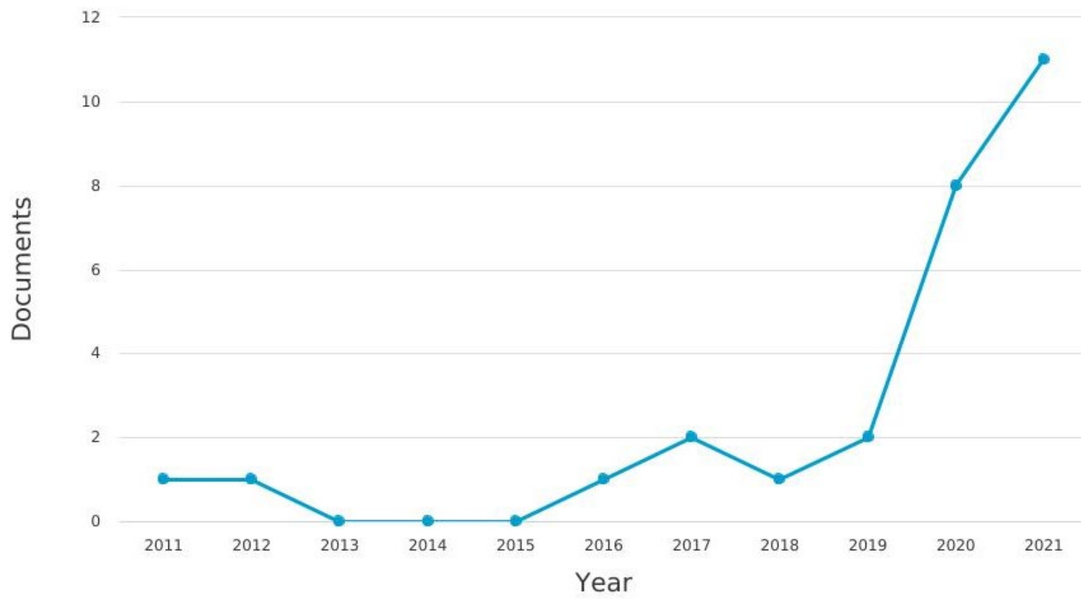


Figure 10: Development of social sciences publications in design principles for safe human-robot collaboration returned by the Scopus search over time

Qualitative analysis: safety measures for collaborative robots

The following sections categorise and summarise safety measures that were identified based on the structured literature review and interview study (see Table 6). The categories are based on the dimensions for introducing cobots into the workplace presented in the background section (see Figure 2). The dimensions "cobot", "working system" as well as "enterprise and context" have been considered to categorise safety measures. The "operator" dimension has not been included since operators are the inherent focus of all safety measures.

Table 6: Summary of safety measures for collaborative robots

Dimensions	Safety measure	Description
Cobot-specific	Cobot type	Lightweight cobots with inherent active/passive safety mechanisms often represent a safer option compared to covert industrial robots to collaborative tasks.
	Cobot appearance	Heavy, stiff, and rigid cobots can cause distress and discomfort within the humans that operate in their vicinity.
	Fail-safe system structure	Integrating general non-safety devices into collaborative systems may cause unwanted behaviours and loss of movement control.
	Tool/design operation	The way in which tools are selected and integrated into the robot can impact the physical safety and psychological state of operators.
	Collision avoidance	Monitoring the working area through a combination of software and sensors allows to avoid and prevent collisions.
	Collision detection and mitigation	When collisions occur, they can be detected and mitigated by a combination of software and sensors.
	Situational awareness	Easily interpretable feedback from the robot allow to reduce both physical and psychological risks.
	Intuitive cobot programming	Intuitive programming and allow operators to communicate commands more easily, reducing both physical and psychological risks.
Working system	Work cell design*	Designing a cobot work cell to work harmoniously with the application, existing workspace, operators, and other staff.
	Human-friendly work distribution	Distributing tasks adequately reduces the risk of physical stress and musculoskeletal injuries.
	Human-friendly workplace arrangement	Arranging the workspace to allow enough distance/space between humans and robots can reduce the risk of collisions and distress.
	Risk assessments*	Systematic evaluation process that considers potential risks and harms that may occur when working with cobots.
	Simulation*	Use of simulation programming to virtually visualise and assess the intended programmed operation for risks and other potential issues.
	Physical testing*	Multi-step process of assessing various components of a cobot to ensure safe operation.
Enterprise and context	Training to build knowledge and skills*	Ensuring that cobot user groups and other stakeholders possess the appropriate competencies, skills, and knowledge to ensure safe operation.
	Training to improve acceptance*	Introducing predictability and familiarity to mitigate physical, psychological and ethical risks.
	Assistive technology for training	Using virtual or augmented reality to prepare and train the operator before they come into contact with cobots.
	Supporting worker agency*	Consulting and co-designing cobot solutions with operators and collaboration between operators and management teams.

**Additional safety measures identified in the interview study.*

Cobot-specific

Cobot type

Two major aspects influence the appropriateness of the robot's choice. The first question to be answered is what enables a robot to work collaboratively. The role of cobots can be categorised based on the International Federation of Robotics (IFR), and differentiated between co-existence, sequential collaboration, responsive collaboration, and co-operational cobots (Dimeas & Sagar, 2021). While the interview study showed varied perspectives among cobot user companies in their understanding of the differences between collaborative and industrial robots and collaborative and non-collaborative applications. Although a collaborative robot is clearly defined as a "robot designed for direct interaction with a human within a defined collaborative workspace". This relatively generic choice of words allows leeway in the selection of a robotic system. The use of robots in a human-robot collaboration is not limited to robots inherently capable of collaborative work. Instead, it can be achieved via any kind of industrial, professional, personal service or even managerial robots (Murashov et al., 2016; Probst et al., 2015; Steger et al., 2018). However, their implementation might heavily differ. Traditional industrial robots must be equipped with adequate additional features before being capable of safe human interaction. This includes, for instance, additional software packages such as Dual Check Safety technology, the Safe Operation or SafeMove solutions of the robot manufacturers FANUC, KUKA or ABB respectively (Magrini et al., 2020). External sensors and safety equipment may also be installed so that the robot complies with one or more of the four collaborative operation modes defined by the ISO 15066. However, integrators that were interviewed did not believe that these forms of safety peripheral equipment adequately addressed the primary risk in working collaboratively with industrial robots. They argued that the higher payloads and speeds at which industrial robots are capable of working were incompatible with safe collaboration.

Compared to industrial robots, cobots offer active and/or passive compliance and lightweight design (Siciliano & Khatib, 2016). These features combined with low moving masses are considered inherently safe for human-robot interaction (Jeske, 2017). As safety-improving niche categories in the field of collaborative robots, tendon-based and soft-bodied robots should be mentioned as relevant alternatives. While the actuators of tendon-based robots are located in the robots' base reducing the weight and subsequently the impact of moving parts (Siciliano & Khatib, 2016), soft-bodied robots provide a natural solution to realise a safe and dependable physical human-robot collaboration (Zacharaki et al., 2020). Finally, affective robotics, which exploits the underlying psychophysiological state of the operator during the interaction, promises to improve the interaction and monitor the well-being of the operator (Villani, Pini, et al., 2018). While such systems are currently discussed for socially interacting and service robots, preliminary attempts have been investigated in the industry-related framework of the INCLUSIVE EU project (Villani, Pini, et al., 2018; Villani, Sabattini, et al., 2018).

When considering what may be the appropriate equipment for a task it is also important to question whether cobots are the most appropriate and safe choice. If the deployment of a cobot is considered, its specific role needs to be decided upon (Dimeas & Sagar, 2021) and according to that, a differentiation between the four collaborative operating modes needs to be made (Platbrood & Goernemann, 2018). In the interview study, an artisanal manufacturing company perceived cobots as another tool in their arsenal. By considering cobots as a tool rather than a co-worker, they were afforded the flexibility to identify the tool that operators were most comfortable with for a job on a case-by-case process. However, this privilege is not afforded to all cobot user companies as for many small-to-medium enterprises, purchasing a cobot is a significant investment that may influence their decision to use cobots where other equipment may be better suited and safer to use. Furthermore, this approach may not be applicable to conventional manufacturing and industrial environments that mass-produce products.

Alongside this, it became apparent in the interview study that cobot users did not have a strong understanding of safe and appropriate human-robot collaborative applications. To mitigate this, suppliers, distributors, and integrators consult with potential customers during the sales process to evaluate whether human-robot collaboration is the most appropriate solution for the task. Encouragingly, the industry has been proactive in ensuring that potential users are purchasing the most appropriate technological solution; with various anecdotes being shared by interview participants of them strongly recommending against the purchase cobots or suggesting additional safety measures so that the cobot can be used for non-collaborative applications including installing fencing around work cells. Therefore, it becomes clear that suppliers, distributors, and integrators have a responsibility to educate customers on the nature of collaborative applications and to provide expert advice on the best automated solution.

Cobot appearance

The second aspect regarding appropriate robot selection is its appearance and how the operator working closely in collaboration perceives it. The desire for close physical human-robot interaction has created a paradigm shift in the design of cobots. While the heavy, stiff, and rigid design with potentially disclosed actuator and wires of traditional industrial robots can make humans feel uncomfortable or distressing, the design of cobots emphasises lightweight and highly integrated mechatronics with fewer pinch points and smooth surfaces (Kuehnrich, 2019; Siciliano & Khatib, 2016; Steger et al., 2018; Vysocky & Novak, 2016)(Kuehnrich, 2019; Siciliano & Khatib, 2016; Steger et al., 2018; Vysocky & Novak, 2016). With the growing market of humanoid robots, the trend is to give the robot a human-like appearance. In fact, the acceptance of a robot for HRC generally increases with higher similarity to human appearance (BAUER et al., 2008). A cobot distributor claimed that the anthropomorphic nature of cobot arms was a design feature that helped familiarise users to cobots. However, the importance of human-like features to increase the acceptance of cobots in the workplace was not a strong consideration for cobot users interviewed.

Interestingly, the interview study highlighted the force impedance mode can make cobots feel more “squishy and playful” to users. While this more playful interactivity enables the robot to feel friendlier it does result in less precise manufacturing outcomes. A cobot user explained that in this mode cobots become more responsive to the physical touch of operators which made them begin to empathise with the cobot. They claimed that this response to their physical touch immediately made “the interaction more intimate because you care more…like it’s like a little puppy rather than a rigid arm”. The cobot user was concerned that there may be inadvertent and unnecessary psychological burdens on operators that could be brought on by caring for an anthropomorphic object.

In line with this phenomenon is the effect of the emotional expression of the cobot. Studies have shown that the expression of simple emotions of a cobot is preferable to complex emotions. This can be explained by the fact that complex emotions also lead to the expectation of more extensive intelligence on the part of the system so that people react in a disappointed and demotivating manner if the cobot does not behave as cleverly as expected (Sauppé & Mutlu, 2015). It is, hence, necessary to balance the perceived safety of working with the collaborating robot with the actual safety through the design of the workplace. A case study showed that the use of a Baxter cobot (from Rethink Robotics) which is equipped with a display imitating human eyes (see Figure 11), had a significant beneficial impact on the human’s comfort working closely together (Sauppé & Mutlu, 2015). A similar human design of the cobot was reported of giving a sense of security and comfort as well as provide the robot with predictability. Training could help operators understand the mechanics of cobot movement which inherently can be used to predict possible movements of cobots. This may help to ease their fears of unexpected movements and collisions.

Another case study (Cao et al., 2019) about robot-enhanced therapy highlighted the impact of social-demographic factors on the ethical acceptability in working with a supervised autonomous robotic system for Autism Spectrum Disorders (ASD) therapy. Besides gender or age influencing the acceptability, an interesting factor was if the questioned parents were involved directly with ASD children. The study showed that these parents had a higher ethical acceptance level than those who were directly involved. These findings can be transferred to the industrial environment, by which the selection of the cobot should be made individually dependent on the worker and their attitude towards cobots. Deciding on a cobot system without consulting the actual operator can lead to discomfort and loss of trust. Consultation as a safety measure will be explored later in the report.

Figure 11: Example of collaborative robot appearance (Sauppé & Mutlu, 2015)

Fail-safe system structure

Another significant aspect of developing a safe human-robot collaboration is the appropriate integration of surrounding equipment. As a collaborative workstation may consist besides the robot itself of several external devices such as the sensors, tooling, additional machines or monitoring equipment, their fusion to a functional system is highly important to guarantee the operator's safety. However, such integrated measures may fail and thus, it is necessary to consider complementary protective measures in the system structure to reduce the risk of harming the operator while working within the collaborative workstation (Dimeas & Sagar, 2021; Platbrood & Goernemann, 2018; Soranno, 2020; Soranno et al., 2019).

The greatest risk is associated with the integration of general non-safety-rated devices. To generate a better understanding of the current situation in the workstation, many research approaches tend to implement external camera systems or other monitoring sensors, promising improved safety for the operator. However, such commonly interrogated sensors are often not designed for reliable outputs, which may cause unwanted system behaviours if other components rely on their data in real-time. Monitoring sensors are, however, considered being useful tools in maintaining and troubleshooting integration issues with cobots as noted by several integrators and service engineers in the interview study. Although the technology does not yet seem to be firmly established in the industry, it is seen as a very promising necessity for free and safe movement in the shared workspace and is expected to be adopted in the market in the near future (Schlueter, 2018). Nevertheless, it is important to consider the ethical and psychological impacts upon workers who are being monitored. While (VDMA Robotics + Automation, 2016) and (Steger et al., 2018) point to the important concerns regarding confidentiality and privacy; generally, limited consideration is given towards how data has been collected, stored, and used by cobot user companies and cobot manufacturers. This is a strong concern for cobot user companies that work with vulnerable communities such as medical patients. Monitoring robots that are being used collaboratively inherently implies that operators are being monitored as well. This constant supervision can contribute to a hostile work environment that can further limit a workers' agency in their preferred workflow and increase their distrust to the use of cobots in making their work easier.

A promising approach to overcome the previously mentioned psychological and ethical dilemmas caused by monitoring cameras is to integrate cobots into an overall safe system structure. This could be achieved by procedural and architectural redundancy, a so-called dual channel system, where two unidentical components each complement the safety system (Aldini et al., 2019; Dimeas & Sagar, 2021; Pedrocchi et al., 2013; Prange, 2019; Probst et al., 2015; Soranno et al., 2019; Stengel et al., 2010). In such a secure network, redundant processing units are used to compute individual operational data related to the robots' motion and backs up the individual data dispatching via redundant data streams for an infrastructural redundancy (Pedrocchi et al., 2013). One integrator claimed that "safety is all about sort of building in redundancy. So we've got not just one solution but many solutions that show that you've covered the risk assessment." To enhance the level of safety, it is also possible to integrate redundant sensing hardware, such as two laser scanners working in parallel, which communicate through a safe channel (Magrini et al., 2020). Additional monitoring capabilities and component diversity/redundancy were identified as priorities to mitigate the inclusion of unsafe sensors and associated algorithms in collaborative human-robot tasks (Magrini et al., 2020). Regarding safe work with robot workers, redundant structures play an important role, specifically when interacting with an industrial robot, as its misbehaviour could, in fact, lead to severe injury or even death of the human operator (Murashov et al., 2016). Furthermore, the concept of redundancy is also recommended for safety measures while performing maintenance tasks on robot workers. An appropriate system degradation is another important factor in complex system architectures. While in general approaches, the entire system is turned off once a fault or failure is detected, in some scenarios, it may be still of relevance or even required for the operators' safety to terminate primary or secondary tasks in a degraded state (Zacharaki et al., 2020). A cobot system should hence be designed in such a manner that fail-safe mechanisms will live into it. The reduction of local functionality without influencing other components when failures are detected allows the system to progress safely into a dedicated safe mode. While operating in a degraded state, the system should still be able to inform their companion regarding its current abilities to avoid uncomfortable and embarrassing situations. In that matter, the appropriate middleware, such as the well-established Robot Operating System (ROS), is of great assistance to a seamless interface between hardware and software components (Zacharaki et al., 2020). Finally, several implemented research applications demonstrate that the use of a safety Programmable Logic Controller (PLC) provides reliable communication channels to implement safe logic under hard real-time constraints to ensure the safe operation of the system (Gopinath et al., 2021; Magrini et al., 2020; Paper et al., 2013).

While traditional industrial robots can hardly communicate with the outside world behind safety fences and limited hardware or software extensions, the danger of cyber-attacks increases enormously due to growing system complexity and integration of insecure periphery of human-robot collaborative workspaces. Even though hackers' intention is primarily lead by financial incentives, it cannot be ruled out that human operators are also harmed unintentionally, raising the information security to equal importance as the functional safety (Korfmacher, 2017). In this context, the utilisation of PLCs are reportedly able to reduce the risk of cyber hacks. A cobot manufacturing organisation explained that the PLCs of their machines would offer 256-bit encryption which is considered one of the highest possible levels of encryption. However, the research participants stressed that both manufacturers and users have equal responsibility to take necessary safety measures and precautions to protect themselves. They stated that the manufacturer could do so much to protect consumers against cybersecurity risks, the end user is responsible in handling the data, assessing vulnerabilities and exposed networks.

Tool design / operation

The quintessence of any robotic system lies in its ability to interact with the environment, which is enabled by tools mounted on the end-effector (Buerkner, 2016). In principle, a generalised risk elimination for all environments is not possible or recommended as the tools and according safety measures must be selected in an individual, application-specific manner.

In fact, “the mechanical design of a manipulator has a huge impact on system safety, and one of the main sources of danger for humans is mechanical power [due to its hazardous impact]. […] A more flexible way to ensure safety is to address the problem at a system design and integration level, taking advantage of modern control techniques and sensors” (Aldini et al., 2019). The risk validation is left to the integrator or user, which is assessed based on an adequate risk assessment. Nevertheless, some basic mitigation strategies can be applied to minimise the physical hazards of individual tools. Since the tools are attached to the robot’s end-effector, often procured independently of the robot, the freedom to decide on the design and approach for integration into the overall system offers a decisive margin. Regarding passive measures, similar design paradigms as for collaborative robots apply (Gopinath et al., 2021). This includes, for instance, blunt corners, soft padding and minimal pinch points (Platbrood & Goernemann, 2018), but also a human-friendly appearance to comfort the human working close to the robot. Additionally, several literature suggest that the use of force sensing and monitoring as well as mount protection for the collaborative purpose as safety assurance mechanisms for the gripper (Bi et al., 2021; Platbrood & Goernemann, 2018; Soranno, 2020; Soranno et al., 2019). If a tool creates a hazard by its very nature, e.g., due to high temperatures or freely rotating components, the tool orientation during operation should be consulted in order to reduce physical harm and improve the operator’s comfort (Bi et al., 2021; Michalos et al., 2015). The risks associated with task-specific tooling should be subject to the existing risk mitigation strategies that have been established for the traditional operation of that task and tool.

> *“When it comes to the end effector…you need to tie in the domain of disciplinary action that is informing that approach. So when you're milling a piece of wood, you need to think a bit like a carpenter when you are feeling a piece of metal a bit more like a machinist.” – Cobot user in university robotics laboratory.*

Collision avoidance

The concept of contact avoidance entails ensuring the safety of operators by preventing hazardous contacts through preventive methods and systems (Elkmann & Behrens, 2019; Gualtieri et al., 2021; Schenk, 2011; Steger et al., 2018; Stengel et al., 2010; VDMA Robotics + Automation, 2016; Vysocky & Novak, 2016). The system must be equipped with appropriate sensors and lasers, plus the corresponding software to enable the robot to avoid collisions actively (Dimeas & Sagar, 2021; Platbrood & Goernemann, 2018; Pomrehn, 2018; SICK AG, 2016; Soranno, 2020). The aim is to monitor activities in the relevant working area of the cobot and, if necessary, adapt the cobot’s behaviour to ensure the safety of the collaborating human (Soranno, 2020). In general, three levels of situational awareness can be distinguished.

The lowest level is the perception of elements in the current situation. Although this includes real-time monitoring of the workspace, it does not include the assignment of movements to a human being or objects. Such an approach is often implemented by static areas in the workspace where different robot control mechanisms are realised and thus correspond to the collaborative operation mode "safety-rated monitored stop" defined in the ISO/TS 15066 standard (BSI Standards Publication, 2016). A common embodiment of this protective measure in industrial research applications is implementing safety-rated laser scanners or laser curtains (e.g. (Gopinath et al., 2021)). An alternative can be found in pressure-sensitive floor mats, which are similarly capable of tracking the humans' position (Gopinath et al., 2021; Michalos et al., 2015). While such two-dimensional approaches comply with the defined collaborative operation mode, an increased desire for volumetric and dynamic workspace monitoring methods is given. This can be realised by safety-rated systems as a safety eye (Michalos et al., 2015) or general camera systems. The latter is especially attractive in research due to its low-cost implementation and variety of opportunities (Siciliano & Khatib, 2016). In this context, visual depth sensors can be used to import the human body 3D volume and any moving objects into the same virtual space in which the robot's real-time motion is displayed (Liu & Wang, 2021). Based on the proximity calculation, any potential collision event can be detected and preventively avoided. Other examples include using Kinect V2 sensors inside an open industrial cell to monitor the restricted workspace of the utilised industrial robot (Magrini et al., 2020), or using machine vision and active collision avoidance to generate real-time point clouds of the workspace (Pérez et al., 2020). In the event of a potentially harmful collision, the cobot automatically avoids the human, reduces its speed, or stops. However, low-cost visual camera systems such as the often-utilised Kinect sensors are not rugged enough for industrial applications, especially as these lack certification in terms of safety operation (Magrini et al., 2020) and cannot be ensured that their field of view is free of obstacles (Michalos et al., 2015). Therefore, the above-mentioned systems are all backed up by safety and warning fields defined by laser scanners or curtains in redundant system architecture. To overcome these limitations, another possible approach for collision avoidance is to attach several time-of-flight infrared light-based cameras to the robots' surface to track its proximity to the environment (Tsuji & Kohama, 2019).

The subsequent level of the robots' environmental awareness is given in circumstances where it can identify the human operator in its surroundings. The safety is hence improved by either monitoring human postures or checking conditions (Dimeas & Sagar, 2021; Pomrehn, 2018; Soranno et al., 2019). Different approaches allow to achieve this purpose. With a camera system facing the operation space, the safety of the operator can be ensured by checking for predetermined colour patterns which are assumed to represent human hands (Cherubini et al., 2016). Another method is to use a monitoring system that measures the operator's body posture and position to estimate the human operation conditions (Tan et al., 2009).

Besides tracking the humans' poses to create a dynamic volumetric safe workspace, the ability of a robotic system to read human emotions promises an enhancement of human safety but also an improved functionality of the system in the joint operation (Murashov et al., 2016). The associated research field has been investigating appropriate methods, including behaviour pattern recognition, on-skin sensors or other similar strategies that would enhance the ability of a robot to "read" human emotion. A new approach consists in evaluating human-to-robot trust by allowing the robotic system to choose between a conservative (safe) and an aggressive (efficient) cobot path based on the humans' emotional state (Sadrfaridpour & Wang, 2018).

Finally, predicting human behaviour in the workspace is the highest level of situational awareness that a robotic system set up for human-robot collaboration can achieve. Although this constitutes a promising solution, this appears to be a long way from a real and robust deployment in the industrial environment (Platbrood & Goernemann, 2018). Nevertheless, researchers have demonstrated a safe and efficient execution of a part-delivery task through a human-aware robotic assistant for collaborative assembly (Unhelkar et al., 2018).

Collision detection and mitigation

Compared to the preventive nature of collision avoidance, the concept of contact detection and mitigation deals with the reduction of collision energy in the event of an unintended or unexpected human-robot contact to ensure the operator safety (Dimeas & Sagar, 2021; Gualtieri et al., 2021; Soranno et al., 2019). However, since physical contact between humans and robots is often important in close cooperation, a distinction must be made between intended contact and accidental collision (Dimeas & Sagar, 2021). The actual identification of whether human safety is threatened remains a key problem of human-safe planning and control methods in the field of robotics (Siciliano & Khatib, 2016). An example of using intentional contact to improve the operator's safety and comfort is represented by a case study in the context of teleoperated minimally invasive surgery. Working closely to the redundant robot, the operator is able to use the extra degree of freedom of the robot to swivel its body towards a more comfortable position without affecting the end effectors pose (Su et al., 2018). This demonstrates simultaneously that the concept of compliant control is a strong enabler for the passive mitigation of emerging external forces applied to a robot. Due to the rendered capability of mechanisms in absorbing part of the energy during a physical interaction, compliance by design or control provides a safety-enhancing technique for human-robot collaboration (Siciliano & Khatib, 2016). Similarly, compliance navigation is likewise the subject of current research in robotics for mobile platforms (Zacharaki et al., 2020). To empower a robot with collision detection capabilities, the safety strategy calls for different equipment (Aldini et al., 2019; Elkmann & Behrens, 2019; Schenk, 2011; Vysocky & Novak, 2016). This include proprioceptive sensors, tactile/capacitive skins, or visual perception methods (Michalos et al., 2015; Siciliano & Khatib, 2016). For example, an admittance controller based on the robots' proprioceptive force/torque can be used to detect any external wrenches in the context of collaborative manufacturing. Once the external wrenches exceed a defined threshold, the robot either conducts a safety stop or changes its waypoints depending on the current phase of the task (Cherubini et al., 2016). While robots marketed as collaborative robots such as the KUKA IIWA or UR cobot series provide force/torque sensors in every joint to track external impacts, conventional industrial robots only rely on position encoders. In the latter case, collision detection capabilities can be enhanced based on the encoders data using extended state observer (Ren et al., 2018) or neural networks (Sharkawy et al., 2020).

Situational awareness

Similar to the situational awareness of the robot to avoid collisions, the humans' understanding of the happening during collaboration is at least equally essential to ensure their safety. Therefore, (Soranno et al., 2019) emphasize the importance of the communication between cobot and operator, and point out that awareness means should be implemented "where appropriate to inform affected persons of hazards." (Soranno et al., 2019). This necessity is reinforced by the increasing autonomy of the robot, which tends to reduce further the human participant's awareness of their team's actions (Gombolay et al., 2017). As an unpredictable behavior of the robot could cause unpleasant human reactions like fear, shock, or surprise (Murashov et al., 2016), it is crucial to inform the operator of the robot's intended behavior (Kuehnrich, 2019; Schenk, 2011; Soranno, 2020; Soranno et al., 2019; Steger et al., 2018). Notifying the human operator before each movement is very important to reduce mental stress effectively (Arai et al., 2010). Such notification can come separately or in combination in the form of text, spoken words, visual signals, symbols, diagrams or other warnings, that the affected operator definitely understands as a warning or informational sign (Soranno, 2020; Soranno et al., 2019). Furthermore, due to the increasing complexity of robotic systems and their potential to switch between different modes during collaboration, Operator's mode awareness is also considered very important. Besides a comprehensive situational awareness, the operator should keep track of the current mode, know when and how to change the mode, and understand the function of each mode (Gopinath et al., 2021). Improperly designed systems could cause an increase in cognitive demands on the operator. Maintaining situational awareness is also critical in mitigating risks that can occur in environments where cobots are configured by multiple users for various tasks, such as in educational contexts or for experimental manufacturing.

The impact of situational awareness was investigated in a study about LED-equipped robotic drones showing the intended next flying direction. While participants appreciated the communication of high-level flight intent, even when the robot made “errors”, there is potential to inform the operator about the current state and planned robot actions in more effective ways (Szafir et al., 2015). An interesting approach to provide additional information about the collaboration is using the robot head screen and a computer screen (Sadrfaridpour & Wang, 2018). Besides some important task information on the computer, both screens visualised the robot’s simulated emotion through a graphical facial expression, imitating feelings like happiness, worry, or boredom (see Figure 12). This feature as well as the robot’s eyes following the human’s hand, were reported to significantly improve the humans’ trust during collaboration due to the naturalness and intuitiveness of interpreting facial emotions. An example of a superordinate classification of the operator distinguishes between beginners and experts and designed the tablet screen showing crucial information about the robot’s state and next intentions accordingly (Pérez et al., 2020). While the screens visualise figures, 3D animations and informative text of each step for beginners, the latter was left out for expert users. Beyond the visualisation of additional information on screens, digitalisation nowadays offers more far-reaching tools. Using smart glasses or projections into the workspace, prepared work plans and instructions can be created for specific situations, reducing the corresponding workload for workers searching for relevant information (Jeske, 2017). Finally, in an case study it has been found that while visual monitoring often means taking attention away from their own work, operators learned intuitively to interpret the sound and rhythm of the robot’s work, identifying patterns of mistakes that demanded their attention (Sauppé & Mutlu, 2015).

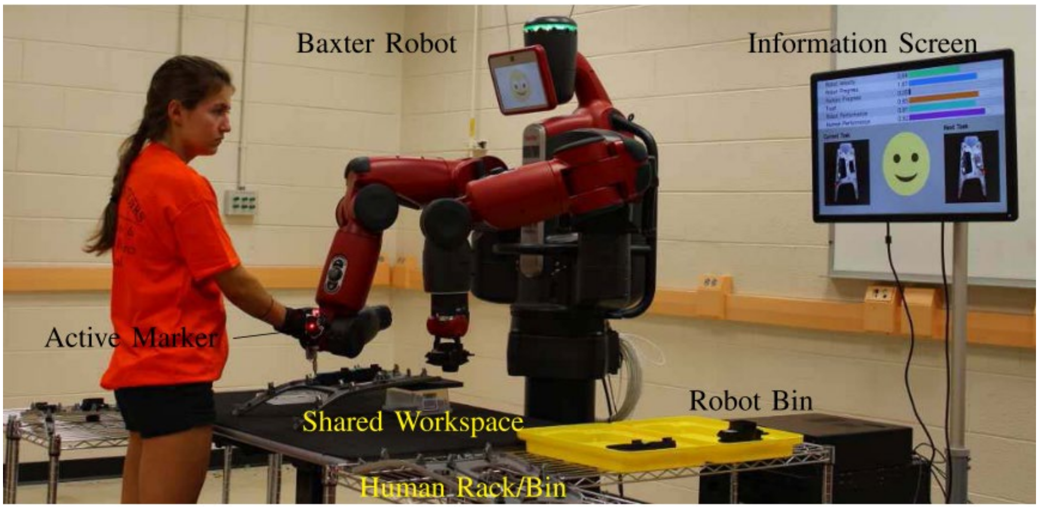


Figure 12: Example of provision of situational information (Sadrfaridpour & Wang, 2018)

Intuitive cobot programming

When programming a cobot, the communication of the human's intention and the correct interpretation of the information from the robot's perspective is a crucial factor (Aldini et al., 2019; Schenk, 2011; SICK AG, 2018; Vysocky & Novak, 2016). It has been found that in practical industrial applications, the programming of the robot consumes a large portion of the human worker's cognitive interaction (Villani, Pini, et al., 2018). The characteristic of a human-robot collaboration that for a human relatively unintuitive information consisting of explicit motion-oriented instructions have to be communicated to the robot makes the procedure considerably more tedious. While traditional programming techniques such as lead-through or coding tend to be quite unnatural, new user interface strategies are emerging that are more closely aligned with a person's native communication channels. Such explicit communication methods include in particular speech, gesture, action and haptic signals (see Figure 13) (BAUER et al., 2008). Thus, the provision of so-called natural and tangible user interfaces plays a crucial role in assisting the operator in the transmission of his/her intention and significantly improving his/her comfort in the once moderate programming of robots. Hand-guided operation was overwhelmingly the most intuitive programming mode for operators to use.

"It was natural just to move the robot in this way…I feel that I am able to communicate better with the cobot…it's all about the interface." - Operator

Besides the simple transfer of information through intuitive communication channels, more advanced approaches such as programming by demonstration and human-in-the-loop are promising concepts for further facilitation of collaboration with a robotic co-worker and reducing the human's cognitive demands (Villani, Pini, et al., 2018; Zacharaki et al., 2020). By including deep learning procedures, the cobot improves its collaborative abilities and can for example, detect and react more safely to involuntary contact with the operator (Dimeas & Sagar, 2021).

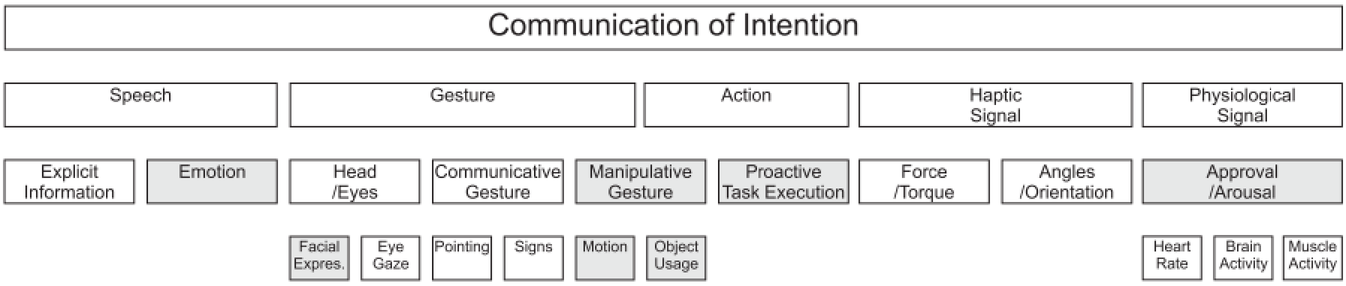


Figure 13: Means of communication (implicit communication is marked grey) (BAUER et al., 2008)

Working system

Work cell design

Considering the design of work cells can minimise the risks of hazardous collision and debris. Light curtains were consistently reported as a safety peripheral device that prevented workers from accidental collisions. Furthermore, graphic signs and markings on the floor visually reminded workers of the importance of maintaining distance from actively operating cobots. However, these safety measures cannot mitigate risks of debris as noted by one researcher interviewed. Instead they recommended installing cobots to face corner walls to prevent objects and debris from being thrown across factory floors.

The interview study identified that several users implemented cobots to work dynamically in a workspace or in various settings. To do this, cobots were placed upon devices or vehicles that enabled operators to easily move it around such as trolleys or would install cobots upon autonomous mobile robots (AMRs) or automated guided vehicles (AGVs). When working with mobile cobots, interviewed cobot users would stress the importance of programming the cobot to operate within the boundaries of the vehicle itself. During this process, cobot users would also consider the tool and the task itself in the programming. For robots installed upon tracks, one operator suggested the use of datum switches and limits to create hardware limits that ensure the robot does not fall off the track. Furthermore, this equipment minimises the risk of unexpected movements as it ensures the robot knows “where home is” so that it begins operation at the same point each time.

Human-friendly work distribution

In the planning of an interactive collaboration of several parties, the adequate distribution of tasks is a crucial aspect. Not only to achieve the highest productivity, but also to integrate the individual skills into the collaboration in the best possible way (Aldini et al., 2019; KUKA Aktiengesellschaft, 2017; Probst et al., 2015; VDMA Robotics + Automation, 2016). Generally, “collaborative robots are likely to improve the quality of workplace, as they liberate humans from ‘dull & dirty’ work and allow them to dedicate themselves to more interesting and creative tasks" (Probst et al., 2015). The understanding that cobots will replace ‘dirty, dangerous, and dull’ work was strongly echoed across all research participant groups in the interview study and across literature (Buerkner, 2016; Dimeas & Sagar, 2021). However, while operators reported that their job had become less dangerous and dirty, they mentioned that operating cobots was still a repetitive and tedious task. In case of a human-robot collaboration, it provides unique benefits as both parties have highly distinguished capabilities. On the one hand, humans are notoriously superior to robots when it comes to work that requires fine and adaptive motor adjustments, processing complex information and responding to unexpected conditions, and high flexibility. On the other hand, robots excel in areas that place physical stress on humans, such as work that involves awkward postures and orientations, repetitive motions and sustained forces over long periods of time which are all known risk factors for musculoskeletal injuries and fatigue (Pearce et al., 2018).

To reduce risks to operators in human-robot collaboration, it is important to delegate work appropriately, considering the potential of both parties, with a primary attention to the physical demand and ergonomic comfort of the operator. For instance, a correct rotation or lifting of objects can significantly relieve the collaborating human from monotonous, tiring and physically stressful tasks (Schlueter, 2018). Existing literature proposes several methods to generate task assignments and schedules during the transition of manual to robot-assisted manufacturing processes. These include optimisation-based approaches exploring the trade-offs between minimising the make span and the physical strain on the human worker (Pearce et al., 2018), as well as hierarchical task analysis methods considering factors such as productivity, human fatigue, safety, and quality (Heydaryan et al., 2018). With safety as the dominant aspect, the latter approach has demonstrated a significant reduction of physical workload with the small bottleneck of slightly increased assembly time. Through an appropriate task delegation in the assembly of a homokinetic joint use case, operator load can be reduced approximately by 60%, leading to a reclassification of the assembly cell in the PSA Group (Peugeot Société Anonyme, formerly known as PSA Peugeot Citroën) ergonomics scale from red to medium level (Cherubini et al., 2016).

Designing the operative task to work around humans is especially important in situations where conventional safety measures cannot be used or disrupts other work processes. An example of this is represented by a cobot user that worked in the film industry, where the red light that turned on during robot operation was covered so that it did not interfere with the specific lighting of the set. To work around this, robot operators would brief staff on set prior to commencing operation and would demonstrate robotic movement to actors so that they understood how to interact with the machine. However, the research participant also acknowledged that these measures are dependent on the work environment and so when the situation became complex, they resorted to placing the cobot on standby.

Human-friendly workplace arrangement

Literature proposes different views regarding the arrangement of the workplace. On the one hand, the working space can be significantly reduced by the possible removal of safety fences, representing a potential advantage for the company. Keeping the cell as small as possible avoids unnecessary movements for both the cobot and the human, ensuring an improved ergonomic situation for the operator (Platbrood & Goernemann, 2018). On the other hand, close collaboration with an automatically moving machine exposes the human to a variety of possible risks. Physical harm is caused in situations in which "contact between human and robot is provoked by the human interfering with the path of the robot. Appropriate ergonomic design therefore should allow for the human to avoid such contacts.", (VDMA Robotics + Automation, 2016). Besides the increased potential of physical harm through collision, the proximity to a cobot system poses a high potential for increased mental workload to the operator (Tan et al., 2009). Several researchers have therefore studied the psychological impact on the operator when working next to a moving cobot. In a cellular manufacturing experiment, it has been demonstrated that cobot motion has a significant impact on mental workload and recommend keeping speeds low to minimise the negative impact on the worker (Tan et al., 2009). In this context, some researchers have provided quantifiable guidelines, suggesting that moving speeds should be less than 500 mm/s when approximating to human and the distance between cobot and operator should be at least 2.0 meters (Arai et al., 2010). Other researchers propose more qualitative guidelines, including the need to make proxemic behaviour a function of personal characteristic to maximise the humans' comfort while collaborating with a robot (Zacharaki et al., 2020), and the importance of placing the cobot in the eye-view of the operator (Malik et al., 2021). Thus, similarly to cobot appearance and acceptance, the individual character of the human has to be taken into account. Gender and previous experience in working with cobots were mentioned as possible influencing factors (Arai et al., 2010) Malik et al. (2021).

Testing and risk assessments are the least consistent safety measures practiced by cobot user companies. However, comprehensive testing of cobot processes is critical in mitigating physical risks and ensuring that innovative uses of cobots are safe and appropriate. Testing provides a procedural process to ensure all elements of physical cobot, equipment, task, and workspace are properly considered and accounted for. The interview study amalgamated the various testing procedures practiced and recommended by research participants into a general process of risk assessment, simulation, and tiered physical testing (Buerkner, 2016).

Risk assessments

A critical process that ensures workplaces have a holistic understanding of the possible risks and harms that can occur when working with cobots and provide comprehensive strategies to mitigate hazards. Risk assessments are typically perceived as a static task that is completed prior to operation. However, risk assessments are a continuous process that respond to the dynamism of workplaces, constantly re-evaluated to assess changes to the workplace including but not limited to changes to the; physical cobot, equipment attached or working with the machine, staff, work cell/setting, operative task, and/or collaborative task. Integrators in the interview study recommended that during the risk assessment process that stakeholders in the cobot industry (see Table 4) should be consulted with to ensure that the assessment is as comprehensive as possible.

Prior to the conventional risk assessment, integrators, suppliers, and distributors would assess the collaborative intent of the customers intended application. Integrators would question whether the application possessed a collaborative intent. If customers were unable to demonstrate a clear collaborative intent, research participants would recommend other solutions such as fencing or industrial robots that were better suited for their desired application.

Integrators reported that their risk assessment process was multi-layered, with their first stage of risk assessment being a checklist derived from the special machinery standards, to consider the possibility of operator misuse. They then conducted an "additional risk assessment of the cobot and industrial robot checklist and risk assessment". Integrators claimed that handover only occurred after users had been trained and the risk assessment had been applied. This practice of amalgamating various other work health and safety resourcing was replicated in interviews with user groups. Interestingly, the research participant created a database to systematically maintain and document all risk assessments.

"It started out as a pdf that we made as a sort of student handout a questionnaire as a handout And we're just now translating that into our database that actually stores the risk assessments. ***So it's based a little bit on the kinds of risk assessments of safe work procedures that we have at the university*** *But it is also based on a spec for collaborative robots which was given to us by a robotic Integrator. And then it's also based on the recommendations of KUKA and universal robots." – User*

Simulation

The most common form of testing of task application reported in the interview study was simulation. Simulation software can be useful in mitigating unexpected movements that result in hazardous collisions caused by programming or human errors. Users must configure the program to the appropriately consider the physical space where the cobot will be installed. However, there are severe limitations to the use of simulation for comprehensive testing, especially for dynamic workplaces or for novel uses of cobots. For example, simulating a mobile cobot may be unrealistically time-consuming or simply impossible if a cobot is intended to be constantly used in new work settings such as sites for film or university labs. Additionally, end effectors and other tools are simulated as static objects, this severely limits the tests' ability to holistically assess the cobot system for risks. Therefore, it is recommended that cobot users also conduct physical tests of the task application to assess that the cobot and additional equipment are properly operating and that the machine will not collide with operators or produce unsafe debris.

Physical testing

"Testing is a layered approach of rerunning tasks over and over again, like a rehearsal" – User

The first physical test of a task application should initially be conducted at a slower speed and without end-of-arm tooling and without a workpiece. A user reported that they often recommend running tests at 10% -20% of the intended operational speed. At this stage operators should be primarily assessing the cobot for unexpected movements and collisions that may exist in the workplace that cannot be accounted for in a simulation. In workplaces where cobots are constantly re-configured and programmed by multiple users for various tasks, this stage also ensures that the cobot is operating the intended task of the operator.

The second test maintains the slower speed but evaluates the end effector, other equipment, and the workpiece. This enables the operator to validate that the equipment is appropriately attached and is functioning appropriately. Furthermore, at the slower speeds the test can ensure that cobots are correctly conducting their task with the workpiece and human.

Lastly, a full run is completed at intended operational speed with operators interacting as expected in the task. Although dead-man switches are recommended for all testing, it is most critical in this last stage so that operators can quickly and safely stop the cobot if there are any issues in the test. The interview study heard of multiple forms of these switches including switches on the back of a cobots teach pendant that operators must hold on to or foot pedals. In physical rehabilitation settings, foot pedals enable 2nd party users more agency in deciding when to begin and end operation with a cobot. A cobot user shared their workplaces process of having two operators present during this stage of testing, they explained that "…there's one that is in a separate room basically supervising the one that's on the field and both have emergency stops". This offers an additional layer of safety, especially in mitigating risks associated with debris caused by specific tasks or other issues that have been neglected.

It should be noted that this procedure can be further drawn out to test the task at various speeds and with different tools, however this baseline procedure ensures that most general physical risks are addressed. Simplifying the testing procedure to this basic form also minimises the tedious and time-consuming experience of setting up cobots for end users. The concept of testing kits was also noted during the interview study, where users and risk assessors could evaluate the potential of pinch points using fake fingers. However, this was not mentioned by other research participants.

Enterprise and context

Training to build knowledge and skills

It is important to consider the various competencies, skills, and knowledge that different stakeholders require in order to be adequately prepared to work with collaborative robots (Buerkner, 2016; Fortune, 2019; Saenz, 2019; Soranno, 2020; Soranno et al., 2019). However, prior to exploring what stakeholders should be trained in, it is important to understand who these stakeholders are, their roles and responsibilities, and the broader certification processes that can develop standardised practices to human-robot collaboration (KUKA Aktiengesellschaft, 2017; Steger et al., 2018; VDMA Robotics + Automation, 2016). The intersection of organisational, process, and training design dimensions reveals four primary stakeholder groups that require different forms of training to mitigate risks and harms. These groups are: cobot users, integrators, service engineers, and risk assessors.

To prevent the exclusion of cobot users outside of the conventional manufacturing and industrial contexts; cobot users should not be perceived as a monolithic group by standards and risk mitigation strategies. Two research participants who were experienced in the development of standards explained that risk assessments must consider different user groups and circumstances that cobots can operate in. These sub-user groups include:

- Operators – Users that are aware that the cobot is operating and are directly responsible in operating or supervising the machine.
- Passive users – Beneficiary users that are aware that the cobot is operating but cannot directly change operation. Examples include patient in physical rehabilitation.
- Visitors and other staff– Other staff and or visitors in the space who may be unaware of cobot operation and cannot change operation. Examples include nurses working on the same floor or other residents of a care facility.
- No party - When no one is in the same space as a cobot while it is operating.

A lack of knowledge and experience in operating cobots was largely attributed as the leading cause of increased physical and psychological risks, according to most research participants. Understanding this, it is clear that training and short courses are critical to ensuring that users who are programming, operating, or maintaining cobots remain safe (Murashov et al., 2016; Soranno, 2020; Soranno et al., 2019). The most universal training recommendation for 1st party users from all research participants was for operators to have a clear understanding of cobot movement and an ability to locate and operate emergency stop mechanisms. Furthermore, training should educate users on the most common risks and harms that can occur while interacting with cobots. For a cobot user that provides basic training courses for university students these main considerations are; pinch points, collisions, offline and real-time operation, and collaborative intent. They also stressed the importance of understanding the complexity of “kinematic planning and the complexity of computing the movements that you want the robot to make”. Training for task and industry- specific applications can be provided through specialist short courses or through consultations with integrators and industry partners. For second- and third-party user groups, integrators suggested than instead of cobot-specific training, these users were simply trained in safely working in the setting itself.

Overall, categorising user groups by operational agency and their awareness of cobot operation holistically considers the dynamic nature of workplaces and addresses non-industrial and/or unconventional applications of cobots, such as integrating cobots in an aged care facility. However, to comprehensively address the organisational and process design dimensions of the cobot system, this report suggests administrative staff and management as an additional user group. Although administrative staff and management may not actively interact with cobots, they are responsible in establishing workplace processes that ensure the safety of other user groups when working with cobots. Integrators from the interview study strongly recommended that administrative staff attend short courses that introduced them to cobots systems and safety. These courses could outline cobot-specific risks and harms that may occur, emerging best practices for cobot safety, and/or provide safety documentation and resources such as risk assessments templates.

For managers, it appeared that training was focused on strengthening leadership skills that support a workplace as they introduce cobots. Interestingly, a researcher that was interviewed highlighted the importance of building learning cultures to support the safe and sustainable growth of cobot integration in Australia. In order for them to lead this change, managers also needed to understand the possible changes that human-robot collaboration introduces. The same research participant recommended that middle managers and administrative staff engage in micro-credential safety courses that conduct skills inventory and skills strategy exercises.

> *"I think they need a whole new knowledge paradigm to understand the new generation of risks and threats and [understand] how people are going to be affected. I think if you could have a two-day primer in the world of Cobots for health and safety officers and what the new generation of risks, threats, mental health issues and training requirements. I don't know if it's two days, it might be a week, it might have to be six months, but I think once they get that new skill set, I don't really see robotics in general and Cobots being any different to any other industrial revolution" - Researcher*

Training to improve acceptance

Considering the emerging nature of cobots and their growing use, finding ways to introduce predictability and familiarity into the cobot system can be beneficial in mitigating several different physical, psychological, and ethical risks. Therefore, alongside the physical design of cobot, it is important to consider training to help cobot users and operators feel more comfortable working with cobots. Comfort is based upon predictability and familiarity, both of which minimise the mental strain that operators experience when they are fearful of cobots. Training can help reduce mental strain as it enables operators to better predict cobot movement. A service engineer explained that operators are first taught to understand how cobots move as "once I learn what robots are doing, I tend to be more predictive about if it's going to crash or not when I'm testing and commissioning the first time round". A worker's sense of comfort and acceptance of cobots in the workplace can be developed by becoming more familiar with the machine. Familiarity can be developed through a sustained working experience with cobots. While formal training is a crucial risk mitigation strategy; many of the cobot users interviewed claimed that their sense of comfort and acceptance of cobots was developed by on-the-job learning and demonstrations.

> *"Yeah, a lot of people haven't worked with robots themselves first time. So we find that they are really interested in the training sessions. There's a bit of fear as well that comes along with that… we try to show them demonstrations and show how safe it is and generally that's quite an easier way to break through with them [operators]. Especially after using it on site, those barriers that they see generally fade quite fast." - Integrator*

It should be noted that familiarity can also create work-health complacency. One possible strategy to address complacency is by requiring re-certification for operators. This has the added benefit of establishing a baseline expectation of what skills, knowledge, and competencies stakeholders must possess to work with cobots. The adoption of something similar to the SafeWork NSW's 'white card' may be something important to consider for regulators. The idea of a license surprisingly was quote controversial among research participants, with one researcher being strongly against the idea of a cobot license as it could not guarantee that the training would be used consistently. However, an integrator considered it an interesting concept that placed more responsibility on the operator and ensured that they are skilled, experienced and trained to a certain degree to be able to operate the machinery. The integrator was concerned that this would not mitigate risks that occur for 2nd and 3rd party users who may interact with cobots in a shared space but are unaware that they require licensing to operate. Research participants were more receptive to the idea of a "skills matrix test" that demonstrated an operator's experience and competency with the specific application.

Less controversial than the notion of a cobot license for users was the call for standardised certifications and qualifications among integrators and risk assessors. There was a considerable variance across the interview participants when asked about the expected minimum qualifications. Some had already been trained and certified for functional machine safety and safety courses specific to collaborative robotics.

Assistive technology for training

An emerging opportunity to prepare the operators before they come into contact with their physical robotic counterparts is given through the use of virtual or augmented reality. Such technology was investigated for industrial applications, with the most promising uses being reported for design, assembly, and maintenance procedures (Villani, Pini, et al., 2018). The alternative through simulations also takes a vital role in current manufacturing industries, as they ease the engineering of different production lines while providing visual analysis tools for the design of the production process (Heydaryan et al., 2018). However, such reality enhancing technology provides additionally the unique opportunity to train the operator in a realistic but highly safe environment. In this context, Malik et al. investigated the user's immersive VR experience in an industry related use case (Malik et al., 2020). With the use of a head-mounted display the benefits for the user were reported in being able to examine the robot reaches, analyse potential collisions, and conduct placement tests to develop safe working conditions. Similarly, Perez et al. explored virtual reality interfaces for industrial robot control and operator training (Pérez et al., 2019). The VR-based human-robot interface (HMI) allowed the operator to test new robot programs and trajectories without being exposed to any danger of physical interaction or mental stress.

Supporting worker agency

Managers play a critical role in supporting their staff by actively working to maintain the agency of their workers. One way that worker agency can be supported is by encouraging staff to optimise their work assignments to their working preferences and to explore how else a cobot can be used. A manager that supervised several cobot operators explained that cobots helped "take away the dumb, boring, and dangerous parts of work and let our crafts people focus on what is most interesting and rewarding to them". The impact of this approach was confirmed by an operator from the same organisation who explained that their sense of safety and trust was developed in their ability to "program it with such personal intent, you are in front of it. You are moving it wherever you need to move it". It should be noted that these research participants work in an industry that produced bespoke products that is able to approach each application with creativity. This mentality cannot always be reproduced especially in conventional manufacturing contexts, where often operators are still assigned repetitive tasks but are unable to be performed by a robot due to the complex nature of the task.

A broader approach to supporting worker agency is consultation and co-designed solutions with operators. Consultation with specialist staff and technician in the development of new collaborative human-robot tasks can provide operators with capacity-building opportunities that present a path for how their skills and knowledge can grow alongside changing industries. This approach by managers cultivates a 'learning culture', inviting operators to have greater agency in the process of introducing cobots into the workplace. This collaboration can also mitigate the mental strain of operators caused by a fear of job loss. A researcher that was interviewed explained that there was a strong focus in many organisations to upskill specialist tradespeople to be become "digitally-enabled". An operator explained that advising pattern markers and robotic engineers enabled them to evolve their work role to become a “keeper of artisanal knowledge” and provided them the time to focus on the creative aspects of their work. Alongside this, consulting with specialist staff ensures that tasks are best optimised for safety and productivity. When cobot integrators consult with expert technicians, they can collaboratively create solutions that address industry, task, or equipment specific risks that may occur. An example of this is in the welding industry, where cobot integrators typically do not possess the knowledge of how to safely set up workspaces so that debris caused by welding is safely managed.

“So a lot of knowledge comes from asking people on staff who work in those roles because we find that that’s where the most information is gained and saves us a lot of time in the future of doing things”- Integrator

Another form of consultation that arose in the interview study was the consistent collaboration between operators and management teams. Managers who use this approach can have a significant impact upon operators who may feel animosity or fear when robots are introduced into their workplace. Managers that acknowledge how disruptive and long the process of cobot integration can be and actively work to best support workers during the transitionary period can greatly improve the social acceptance of cobots in their workplace.

“…Constant consultation was the only way that we’ve managed it [integrating robots]. I would always be available for a meeting with those team members and we had meetings frequently. The would call because they were feeling uncomfortable, anxious, or uncertain about their role.…I might have thought we got to a more comfortable place, but then a month or six weeks’ time we would have another meeting. Obviously I realised that this was an ongoing process and it’s still an ongoing process” – Manager

Discussion

Based on the findings, three areas are explored in this section. Firstly, the gaps in cobot-related industry standards, underlining the need for developing safety guidelines that include and complement existing standards. Secondly, the attitudes and behaviours of individuals and the industry towards human-robot collaboration. Thirdly, the requirements and design principles in deriving safety guidelines based on the mapping of cobot-specific risks and safety measures.

Observed gaps in cobot-related industry standards

This section outlines areas in cobot-related standards that require better clarification or stronger consideration. As highly technical documents, standards can be difficult for even the most experienced and knowledgeable cobot industry stakeholders to understand and practice. To address this, there are various strategies to improve compliance with standards including; training, stakeholder collaboration, and the importance of research translation increase accessibility for end users.

The study interviewed two research participants from an independent organisation that contributes to the development of standards for new technologies. The largest gap that the research participants identified in their work was that the standards for cobots were primarily developed for industrial and manufacturing contexts, neglecting to account for risks and harms that may occur in commercial or consumer environments (i.e., workplaces). They were particularly concerned about how the safety voltages of the industrial contexts differs from commercial and consumer environments. The research participants explained that in industrial and manufacturing contexts, there are pre-existing electrical infrastructure to support powering heavy machinery, this includes safety measures that mitigate potential electrical hazards and risks such as electrical fires and short circuiting. Furthermore , a by-product of the standards strong focus towards male-dominated industries such as manufacturing is the bias towards defining safety measures to the physical specifications of the 'average' adult man. This excludes a myriad of different people including but not limited to the; young, old, frail, and/or women. This is critical to address in future iterations of the standards as cobot innovation begins to expand into industries that are more balanced representation of the general public such as medical and health services.

Integrators and industry partners recommended that there was a greater consideration for functional safety in cobot standards. The functional safety of cobots ensures that the internal cobot systems can accurately identify and mitigate technological failures before it becomes a risk to operators and the work cell (Intel, 2022). A stronger focus on functional safety would ensure greater safety and compliance of the microelectronics and circuitry itself of the robot.

Consistently, research participants from all stakeholder groups reported that the standards were inaccessible to cobot users. The highly technical language limited cobot users from appropriately addressing physical risks and prevented them from complying with standards. Several research participants recommended training courses can be a useful tool in translating the recommendations of the standards into safe practices. Furthermore, to ensure greater compliance with standards in practice and collaboration between various stakeholders was seen as a useful strategy.

Attitudes and behaviours towards human-robot collaboration

Several research participants reported that their safety procedures and expectations were largely built upon a foundation of 'common sense'. An interesting representation of the "Can I sleep at night test" that one cobot user used to assess the risks and hazards of a situation by their intuitive reaction to the application. They explained that as their cobot application and workspace would dynamically change, this was the best tool that they could use to assess the safety of the collaborative task. However, this creates a dangerous assumption that expects all stakeholders to possess the same intrinsic knowledge and understanding of safety practices. What may appear to be common sense to one individual can wildly vary to another, especially considering the differing attitudes and behaviours one may have depending on their culture, industry, and individual workplace.

Cobots are marketed as safe which leads many users, who are not well-versed in safe robot collaboration, to the misunderstanding that they are safe for every application. A cobot user responsible for training stressed to their trainees that "it isn't a collaborative robot until we establish those basic kind of safety and interactivity requirements that warrant it to be a robot that we can interact with". Alongside this, there is an assumption that because cobots are unlikely to cause severe harm that they are inherently safe to all risks and harms. A researcher encapsulated this attitude by stating that "yes you'll get a bruise but you're not going to die". This behaviour to underplay the severity of risks can lead cobot users to not conduct an appropriate risk assessment that would enable them to place adequate safety measures.

Manufacturers, suppliers, and integrators were less receptive to the suggestion of greater regulatory intervention in the industry. Their concern being that prescriptive measures would stifle innovation that would limit the growth and application of cobots for industrial and manufacturing contexts. However, when the research team asked a 3rd party risk assessor how they addressed this argument that safety stifled innovation; they answered that "safety is what enables technology to become mainstream". Furthermore, the research participants were interested in the future innovative applications of cobots demonstrated in their expansion of the cobot standards for commercial and consumer contexts so that the technology could be applied to new contexts.

Collaboration is a vague term that can be interpreted in various ways. In the interview study most cobot users did not use their cobot for collaborative applications. Instead, most cobots were used for co-existent and cooperative functions with human workers. Research participants that were responsible for selling cobots often stated that the main selling point is that cobots are cheaper, easier to use, and take up less space on factory floors compared to industrial robots. It appeared for several of the cobot user companies that what they were interested in with the technology was less so about collaborative applications and more so the ability to utilise these safety measures to create fenceless applications that free up expensive factory floor space for other uses. It enables workers to safely work alongside automated processes. A safety peripheral manufacturer that converts industrial robots for collaborative use explained that for many of their clients, the desire to purchase their equipment was so that they could go fenceless. Fences they explained were "a hindrance to good flow through".

Requirements and design principles for cobot safety guidelines

The literature and the interview study highlighted two important requirements for cobot safety guidelines. Firstly, the guidelines should engage stakeholders across multiple levels, both within the organisation and outside of it. This allows not only to maintain awareness about safety aspects on all level, but also to promote social acceptance and foster a learning culture. Secondly, items should cover all relevant risk dimensions, i.e. physical, psychological, and social. While most existing measures address physical risks, particularly hazardous collisions, only few address psychological risks, and even fewer address ethical concerns. As future safety guidelines aim to adopt a comprehensive approach that extends across multiple dimensions, it is important to define specific gaps upon which safety principles need to be built.

Based on the risks identified in the phase 2 report (see Table 1 and Table 6), Table 7 maps the safety measures against the risks for collaborative robots. The mapping identifies which risks are not addressed by existing safety measures and highlights the key points future guidelines would need inclusion. The following sections discuss in detail how the risks can be mitigated through existing safety measures.

Table 7: Risks vs. safety measures for human-robot collaboration

		Physical risks						Psychological risks			Ethical risks			
		Hazardous collisions	Cybersecurity	Lack of focus	Loss of movement control	Debris	Pinch points	Mental strain	Lack of trust	Complicated interaction mechanisms	Social environment	Social impact	Social acceptance	Data collection
Cobot	Cobot type	x					o							
Cobot	Cobot appearance							x	x					
Cobot	Fail-safe system structure		x		x									
Cobot	Tool/design operation	x				*	x	x						
Cobot	Collision avoidance	x						x						
Cobot	Collision detection and mitigation	x												
Cobot	Situational awareness	x						x	x	x				
Cobot	Intuitive cobot programming							x	x	o				
Working system	Work cell design*	*				*								
Working system	Human-friendly work distribution	x		x										
Working system	Human-friendly workplace arrangement	x						x						
Working system	Risk assessments*	*												
Working system	Simulation*	*												
Working system	Physical testing*	*												
Enterprise and context	Training to build knowledge and skills*	o						*	*	*		*	*	
Enterprise and context	Training to improve acceptance*								*			*	*	
Enterprise and context	Assistive technology for training*	x								x				
Enterprise and context	Supporting worker agency*								*			*	*	

x – Evidence in the literature review
** – Evidence in the interviews*
o – Evidence in both the literature and the interviews

Physical risks

Most of existing safety measures are designed to address the risk of hazardous contacts with robots. This risk is particularly emphasized as collaborative robots share the same space with operators during tasks. A few design principles also allow to address other marginal physical risks that can lead to physical injuries.

Hazardous collisions

Preventing and mitigating hazardous collisions has been identified as a priority of both existing standards and existing measures. An appropriate selection of the type of robot allows to minimise the risk of injuries caused by unwanted contacts. As opposed to converting industrial robots to collaborative ones, choosing native cobots allows safer interaction with humans due to a lightweight design together with active and/or passive compliance (Vicentini, 2021). The same applies to tools that are mounted on the end-effectors of robots. An appropriate selection of the design and type of integration allows to reduce physical hazards. Even when a tool is inherently hazardous (e.g. freely rotating components), the orientation and speed can be adjusted to allow safer use (Bi et al., 2021).

In addition to selecting appropriate cobots and tools, arranging and designing the workplace in a human-friendly way allows to improve safety. Although small working cells may offer some competitive advantages, the risk of hazardous collisions also increases (Tan et al., 2009). Visual warnings and light curtains around the area can help reminding workers the importance of keeping distant from the robots.

Physical harm can be caused not only by unwanted contacts with the robot, but also by musculoskeletal injuries generated from physical stress such as repetitive motions and sustained forces (Pearce et al., 2018). This risk can be mitigated by allocating a human-friendly distribution of tasks.

More generally, preparing operators adequately before getting into contact with robots allows to reduce the risk of injuries and physical harm. For this reason, training is very important and it can occur in a variety of ways. New technologies such as immersive VR experiences allow to examine the robot reaches and analyse potential collisions in a safe environment (Pérez et al., 2019). However, training alone is not enough to ensure general safety from physical harm. In fact, the two general safety measures specifically designed for this purpose are collision avoidance and collision detection technologies, which are comprised of sensors and corresponding software. The aim is to monitor the working area and prevent and/or detect hazardous collisions.

Finally, risk assessment practices, simulation, and physical tests allow to identify and prevent possible physical risks and hazards generated by a specific working area.

Cybersecurity

Human-robot collaboration systems are characterised by sensors and software that are integrated into the hardware. This makes these systems potentially more exposed to cyber-attacks. Although cyber-attacks are mostly driven by financial motives, the unplanned movements of the robot can cause physical harm to the operators nearby. Using a fail-safe system structure that includes encrypted PLCs allows to prevent and reduce this type of risk.

Lack of focus

A human-friendly work distribution minimises the risk of tasks not being fulfilled as intended that can ultimately lead to physical harm. Allocating tasks to humans and robots appropriately reduces fatigue (Pearce et al., 2018) and thus the risk of lack of focus.

Loss of movement control

Unwanted system behaviours may be caused by a variety of factors among which systems structures featuring general non-safety-rated devices. Fail-safe system structures that include redundant elements have been identified as more promising solutions to address safety concerns (Magrini et al., 2020; Murashov et al., 2016; Pedrocchi et al., 2013).

Debris

Similar to hazardous collisions, debris can be avoided by designing the work cell in a safe manner. For example, some respondents have suggested to install cobots facing corner walls to avoid debris.

Pinch points

Choosing cobots over converting industrial robots also lowers the risk of operators getting caught between moving parts of the robot, as cobots are designed to include integrated mechatronics with smooth surfaces and fewer pinch points (Siciliano & Khatib, 2016). Similarly, the choice of tools to mount on end-effectors can also lower this risk by both passive and active measures such as soft padding and force monitoring systems (Bi et al., 2021; Gopinath et al., 2021). Finally, comprehensive training targeted to first party users should provide awareness around a variety of possible risks, including pinch points.

Psychological risks

Psychological risks are closely related to each other; for example, mental strain and a sense of discomfort can both result from stressful work conditions. For this reason, most of the safety measures that take into account the psychological impact on cobot operators tend to address multiple risks.

Mental strain

The comfort and the mental strain of operators is influenced by several factors including complicated interaction mechanisms, fear of job loss, and a lack of trust towards cobots. Human-like appearance of the robot and the tools attached to it can have a positive effect (Sauppé & Mutlu, 2015). Integration strategies for the tools can also affect the sense of comfort within operators. For example, tools that create hazards due to their nature can be mounted in such way that their orientation during operations can be both safer for operators and increase their sense of comfort (Bi et al., 2021; Michalos et al., 2015).

Similarly, a human-friendly workplace arrangement allows to reduce the psychological impact on operators. In fact, robot motion can have a significant impact on mental workload and keeping speeds low can reduce the negative effects (Tan et al., 2009).

When cooperating with robots, the motion can cause unpleasant reactions to operators, such as fear or shock, that can lead to psychological stress (Murashov et al., 2016). These reactions can be prevented by allowing clear and human-friendly communication modes with the robot (Arai et al., 2010). To increase the level of operator comfort, another measure that has been investigated in some research is the ability of robots to read human emotions. These technologies allow to adapt the system behaviour by interpreting humans emotions (Murashov et al., 2016). Finally, as comfort is based on predictability and familiarity, training can prepare workers in predicting the robot's movements, thus reducing their mental strain during operations.

Lack of trust

Human-like appearance and display of simple emotional expression can positively affect the levels of security and comfort while providing a sense predictability at the same time (Sauppé & Mutlu, 2015). A feeling of predictability of the robot behaviour can also be enhanced by improving the situational awareness (Murashov et al., 2016) through clear communication channels.

Complicated interaction mechanisms

Unclear communication between operators and the robot can cause psychological, as well as physical harm. This risk can be reduced by including interfaces that enable easily interpretable feedback from the robot and intuitive programming from operators (Villani, Pini, et al., 2018). Explicit methods such as speech and gestures allow operators to communicate in a more intuitive way (BAUER et al., 2008). In line with this idea, through appropriate training, when possible managers can actively work to maintain the agency of their workers, encouraging them to tailor their working preferences and explore new uses of the robot.

Ethical risks

There is an evident gap between existing standards and measures and ethical risks. While a growing portion of the literature highlights the ethical implications of introducing cobots into the workplace, existing safety measures do not address these concerns in detail.

Social impact

Training for managers can have a positive influence on social impact. Constant collaboration with their staff allows to foster a learning culture while bringing different stakeholder together. Ultimately, training provides the opportunity to understand the potential changes that human-robot collaboration introduces, including changes in workers' role. As a result, managers can promote the adoption of collaborative robots as an assistive tool, instead of a possible replacement of the operators, which can reduce the fear of job loss among workers.

Social acceptance

On-the-job learning together with demonstrations can create a sense of familiarity within workers and improve the acceptance levels among them. More generally, a consistent collaboration between operators and managers can positively influences the social acceptance during the transitionary period.

Design principles for safe human-robot collaboration

The purpose of safe cobot design principles (Table 8) is to provide overarching guidance on what entails and supports a safe cobot workplace. Their abstract nature ensures that they are applicable to all socio-technical aspects of a cobot workplace and across its entire life cycle. Thus, they are the foundation of the new cobot guidelines, which will interpret and detail each design principle according to its focal life cycle phase and target audience.

The design principles were derived from literature and interview findings of this project. The responsible research team consisted of an engineer, a designer and a work health and safety representative to ensure a holistic socio-technical and regulation perspective. The process of deriving the design principles itself was iterative. First, one team member developed a first set of draft design principles by analysing the harm and risk categories concerning inherent success factors. This led to eight draft design principles and their mapping to risks and harms. Second, the other two team members reviewed this draft document independently, followed by a team discussion, where the draft design principles were revised and enhanced based on the different backgrounds of the team members. This led to five safe cobot design principles, which are described in Table 8. The detailed mapping table, which also includes the revised original draft design principles as sub-principles, can be found in Appendix B.

Table 8: Design principles for safe human-robot collaboration

Design principle	Description
Understand cobot and safety features	Have an understanding of what your cobot can and cannot do in terms of tasks, behaviour and safety features. Have an understanding of how your cobot system ensures safety and how activities might trigger unwanted safety features. Ensure everyone in your workplace has the same understanding.
Ensure a human focus	Consider different cobot experience levels of operators and 'temporary workplace visitors'. Involve your staff in the cobot workplace design to maximise the benefits for them and provide upskilling and social contacts. Be realistic about workforce implication of introducing cobots.
Align cobot, workspace and workflow	Build an understanding that the cobot is only one part of a socio-technical cobot system. Treat cobot, end-effector tools, workplace and workflow processes as an interconnected system, which needs to be aligned to ensure safety ("cobot readiness" of all parts).
Ensure security and protection	Prevent and identify unallowed tempering with cobot hardware and software. Look out for potential issues and consequences of tampering on the cobot, human, end-effector tools, workplace and workflow processes. Ensure that the cobot does not cause any harm in case its hardware or software fail.
Support ease of use	Ensure the cobot and its safety features are user friendly and support the staff's work and do not impede it. Ensure that the positive and negative impact of engaging with the cobot is considered.

Conclusion

The characteristics of collaborative robots bring together a unique combination of social and technical dimensions, calling for safety measures that go beyond mitigating physical risks. Based on the findings of this research and "Work health and safety risks and harms of cobots", it can be concluded that existing standards and practices focus predominantly on mitigating physical risks. Recent studies report a growing interest in psychological and ethical risks. However, this is neither reflected in the existing standards, nor the safety measures.

Existing safety measures can be categorised into *"cobot"*, *"working system"* as well as *"enterprise and context"*. Safety measures directly related to cobots include cobot type, appearance, fail-safe system structure, tool/design operation, collision avoidance, detection and mitigation, situational awareness and intuitive programming. Safety measures covering the working system of cobot and operator include work cell design, human-friendly work distribution, human-friendly workplace arrangement, risk assessments, simulation and physical testing. Enterprise and context-related safety measures target training and consultation, including training to build knowledge and skills as well as to improve acceptance, assistive technology for training and supporting worker agency.

The mapping of cobot-related risks and safety measures shows that physical risks, and particularly hazardous collisions, are covered by a wide range of safety measures. In contrast, other physical risks such as cybersecurity, lack of focus, loss of movement control, debris and pinch points are addressed to a much lesser extent. When it comes to counteract psychological risks, mental strain is covered in a range of safety measures across all three categories – although not as extensively as hazardous collisions. Lack of trust and complicated interaction mechanisms, however, have not been addressed as thoroughly to date. Safety measures to mitigate ethical risks have not been covered extensively in literature, while the interview study revealed enterprise and context measures related to training and supporting worker agency.

It is interesting to see that safety measures directly related to the cobot have been covered mostly in standards and literature. To mitigate risks in the working system of cobot and operator, literature and interviews have both revealed a range of safety measures. Enterprise and context safety measures, in turn, have been almost exclusively addressed in the interview study. The interview study was also able to identify additional measures and applications, which are specifically designed to address psychological and ethical concerns. At the same time, the interview study highlights different layers of stakeholders, and how they can contribute to facilitate a safe transition to human-robot collaboration. This not only demonstrates the effectiveness of this research, but also allows to assist the development five design principles for safe human-robot collaboration:

1. *Understanding cobot and safety features* includes an understanding of what your cobot can and cannot do in terms of tasks, behaviour and safety features as well as an understanding of how your cobot system ensures safety and how activities might trigger unwanted safety features.
2. *Ensuring a human focus* includes considering different cobot experience levels of operators and 'temporary workplace visitors' as well as involving your staff in the cobot workplace design to maximise the benefits for them and provide upskilling and social contacts.
3. *Aligning cobot, workspace and workflow* includes building an understanding that the cobot is only one part of a socio-technical cobot system and, as a result, treating cobot, end-effector tools, workplace and workflow processes as an interconnected system, which needs to be aligned to ensure safety ("cobot readiness" of all parts).
4. *Ensuring security and protection* includes preventing and identifying unallowed tempering with cobot hardware and software as well as looking out for potential issues and consequences of tampering on the cobot, human, end-effector tools, workplace and workflow processes.
5. *Supporting ease of use* includes ensuring the cobot and its safety features are user friendly and support the staff's work and that the positive and negative impact of engaging with the cobot is considered.

These design principles will inform the next phase of this research developing guidelines for safe human-robot collaborative work.

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Appendices

APPENDIX A: Work Package 3 – Sample Interview Question Guide

Thank you **[name]** for making time to speak with us. I'll start by acknowledging the traditional owners of the lands where I'm meeting you today the dharug and guringai people.

Just to give a quick summary, this interview sits in our discovery phase, and the purpose of today is to understand how you approach and practice safety when working with cobots and learn more about what could be improved across the industry.

There isn't any right or wrong answers – and everything shared today will of course be confidential and anonymised before it is shared with the rest of the project team.

Are you happy to continue? Y –Great N – END *(do you know anyone else who may be interested in helping us in this project?)*

Would it be okay with you if I record our conversation for note-taking purposes?

Y – Great, thank you [**BEGIN RECORDING]**

N – No problem at all! Please excuse me as I scribble down some notes as we speak.

Before we start, Do you have any do you have any initial questions?

So let's get started, tell us a bit about yourself and your role?

What does safety mean to you?

How would you define a safe human-robot collaboration?

What safety measures do you believe are important when working with robots collaboratively?

What are some common mistakes you see when people work with robots collaboratively?

How can we address these mistakes?

What are some of the barriers to safe operation?

What is guaranteed as safe to customers when purchasing cobots?

Are there psychological harms that we need to consider?

Are there ethical considerations that need to be addressed?

What is the end users responsibility?

What is your responsibility in practicing safety?

What is missing in the international standards?

How can we encourage innovation without increasing the risk of harm?

What are some blind spots in Cobot industry?

What are some essential principles that every cobot user should know?

What should be included in our guidelines?

Outro: Well, I think that is all the questions that we have for today – thank you so much for your time today and for your insightful responses.

Now, later in the research project we are looking to run some co-design workshops and work with people from across the industry to develop a set of guidelines that will address different groups. Would you like for me to keep you in the loop about this and the progress of our research in general?

Y – Excellent I'll note that down

N – No problems!

We are also looking to engage with a wide range of people in the cobot ecosystem including researchers, cobot manufacturers, distributers/integrators, and cobot users. Do you know of anyone else that you believe would be useful for us to speak to?

[END RECORDING]

APPENDIX B: Mapping of design principles for safe human-robot collaboration against risks

		Understand cobot and safety features		Ensure a human focus		Align cobot, workspace and workflow	Ensure security and protection		Support ease of use
		• Have an understanding of what your cobot can and cannot do in terms of tasks, behaviour and safety features. • Have an understanding how your cobot system ensures safety and how activities might trigger unwanted safety features. • Ensure everyone in your workplace has the same understanding.		• Consider different cobot experience levels of operators and 'temporary workplace visitors'. • Involve your staff in the cobot workplace design to maximise the benefits for them and provide upskilling and social contacts. • Be realistic about workforce implication of introducing cobots on peoples work.		• Build an understanding that the cobot is only one part of a socio-technical cobot system. • Treat cobot, end-effector tools, workplace and workflow processes as an interconnected system, which needs to be aligned to ensure safety ("cobot readiness" of all parts).	• Prevent and identify unallowed tempering with cobot hardware and software. • Look out for potential issues and consequences of tampering on the robot, human, end-effector tools, workplace and workflow processes. • Ensure that the cobot does not cause any harm in case its hardware or software fail.		• Ensure the cobot and its safety features are user friendly and support the staff's work and do not impede it. • Ensure that the positive and negative impact of engaging with the cobot is considered.
		Know your cobot	**Know your cobot's safety features**	**Be human aware**	**Build a team**	**Consider the cobot system as a whole**	**Protect your cobot**	**Fail safe**	**Ease of use**
		Have an understanding of what your cobot can and can't do in terms of tasks, behaviour and safety features	Have an understanding how your cobot system ensures safety and how activities might trigger unwanted safety features	Consider different cobot experience levels of operators and 'temporary workplace visitors'	Involve your staff in the cobot workplace design to maxime the benefits for them and provide upskilling and social contacts	Robot, tools, workplace and processes need to be aligned to ensure saftey ("cobot readiness" of all parts)	Prevent and identify unallowed tempering with cobot hardware and software, and look out for potential issues	Ensure thet cobot does not cause any harm in case its hardware or software fails.	Ensure the cobot and its safety features are user friendly and support the staff's work and do not impede it
Risk consequence	**Risk**								
Physical	Hazardous collisions	■	■	■		■		■	
	Cybersecurity						■		
	Lack of focus			■					■
	Loss of movement control		■					■	
	Debris*					■	■	■	

	Pinch points*								
Psychological	Mental strain								
	Lack of trust								
	Complicated interaction mechanisms								
Ethical	Social environment								
	Social impact								
	Social acceptance								
	Data collection*								