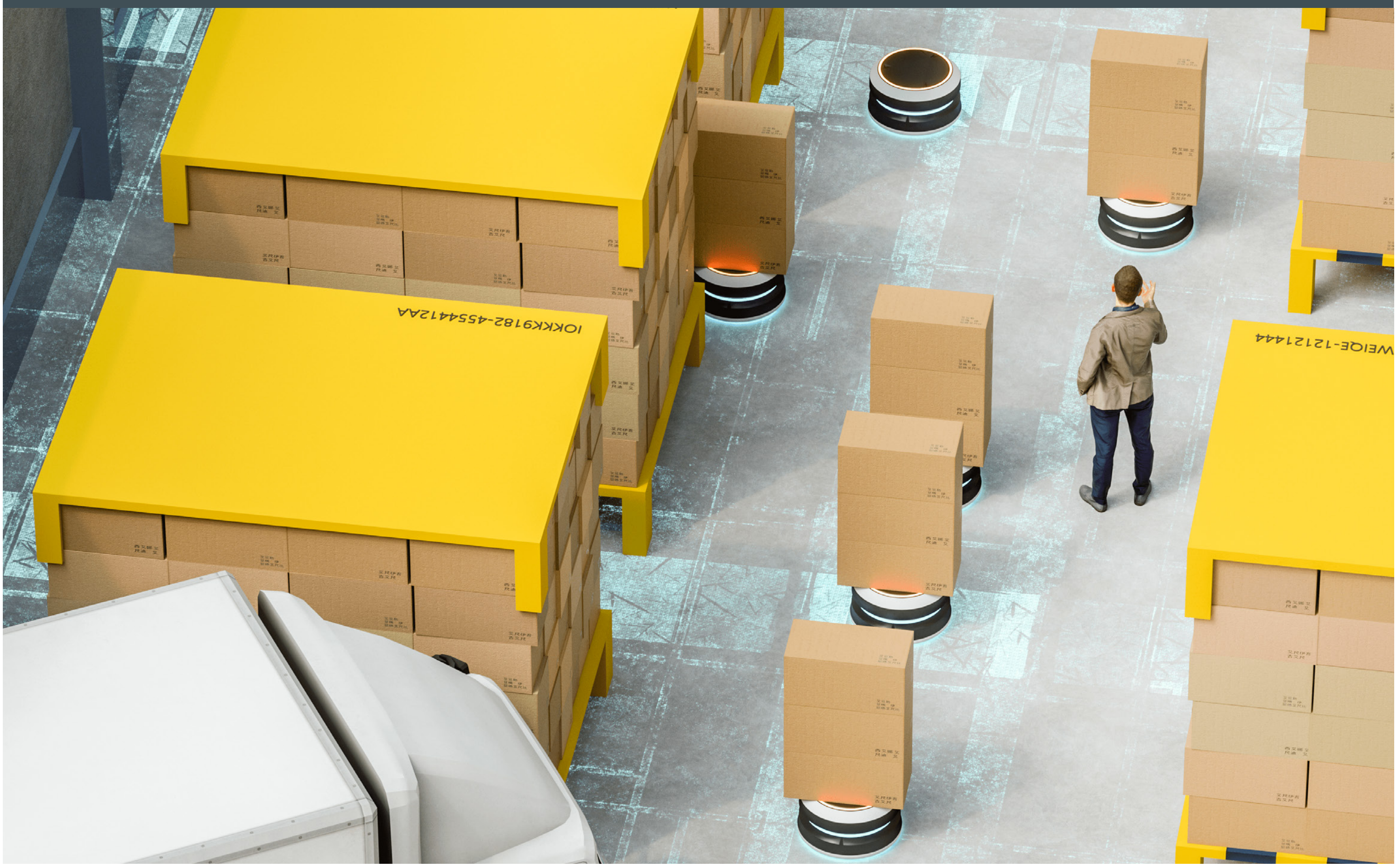
NSW GOVERNMENT

Working safely with collaborative robots: Work health and safety risks and harms of cobots



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Prepared by:

Manisha Amin[1]

Jane Cockburn[2]

Marc Carmichael[3]

Leila Frijat[1]

Rebecca Grace[1]

Matthias Guertler[3]

Sazzad Hussain[4]

Gavin Paul[3]

Nathalie Sick[3]

Laura Tomidei[3]

Annika Wambsganss[3]

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[1] Centre for Inclusive Design, Ultimo NSW 2007

[2] Kairos Now, Manly NSW 2095

[3] University of Technology Sydney, Ultimo NSW 2007

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

Executive summary

Background

While industrial robots have been around for decades, only in recent years have we seen the rise of collaborative robots (cobots). Unlike conventional industrial robots, cobots are designed to be operated in a shared workspace with humans. Although these collaborative settings provide benefits such as the reduction of physically demanding tasks for humans, a new range of risks and harms needs to be considered when introducing cobots. While physical risks, such as hazardous collisions, have been extensively studied and were paramount in the development of cobots, less known forms of risk exist, such as cognitive risks, emotional stress or socio-economic risks. Therefore, this study sets out to identify and categorise cobot-specific work health and safety risks and harms.

Method

A systematic review of academic and grey literature was conducted to synthesise the state of risks and harms related to the use of collaborative robots in the workplace. Interviews with selected stakeholders were then undertaken to validate and complement the insights from the literature review.

Discussion

Our findings highlight a wide variety of risks and harms towards workers' health and safety, which can be classified into three main categories: physical, psychological and ethical. Most risks are related to physical harm and comprise hazardous collisions, cybersecurity, lack of focus, loss of movement control, debris and pinch points. Yet with the increasing proliferation of cobots, more and more risks related to psychological and ethical harm are emerging. 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. Our findings suggest that traditionally there has been a focus on physical risks related to the use of cobots, with little consideration for psychological and ethical risks. However, in recent years, the latter two categories have gained increasing interest, as the use of cobots impacts various dimensions of work health and safety. An increasing number of studies and projects, including this one, have adopted holistic approaches towards identifying and mitigating related risks and harms, considering the physical, psychological and ethical safety of cobot operators. Additionally, barriers to safe cobot implementation include unclear definitional boundaries and use-cases between cobots and industrial robots as well as an inconsistent approach to risk assessments and testing new task applications, work settings, or end effectors.

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Introduction

Risk assessments and safe work practices are part of everyday work in traditional industrial settings, but these traditional work environments are radically changing through the adoption of emerging technologies. In particular, the emergence of increased automation, an increasing involvement of robots, and collaboration between humans and machines reshape industrial workplaces and their impact on workers. The adoption of collaborative robots (cobots) allows humans and robots to perform collaborative tasks in a shared space (BSI Standards Publication, 2016). Although these collaborative settings provide benefits such as competitive advantages for Australian businesses and the reduction of cognitively and physically demanding tasks for humans (Cherubini et al., 2016), a new and different range of risks and harms needs to be considered for workers. In this report, we focus on work health and safety (WHS) risks and harms induced through the integration of cobots. These require understanding and considerable attention with the increasing adoption of cobots in the Australian industrial landscape. Compared to traditional robots, cobots are designed to operate in close proximity to humans and may introduce entirely different or additional risks and harms over the traditional settings, which range from increased collision hazards to psychological discomfort for operators. In order to implement cobot solutions safely, industry practitioners such as cobot users and manufacturers need to be aware of the specific risks and harms and how cobot-specific safety concerns are different from those associated with traditional industrial robots.

Firstly, a systematic review of academic and grey literature (e.g. industry reports and standards) was conducted to synthesise the current state of risks and harms related to the use of collaborative robots in the workplace. This allows the identification of potential synergies as well as possible gaps that need to be addressed in order to develop a holistic approach to worker safety in later stages of the project (i.e. support safe design and implementation). We identified gaps in cobot-specific approaches and best practices from other fields that could be adapted to WHS practices.

Secondly, an interview study was conducted to confirm and expand upon the cobot-specific risks and harms identified in the literature review. Furthermore, the study explored the human factors that contribute to potential risks and harms and determined potential gaps in existing standards and guidelines. Fifteen participants were invited to one-hour semi-structured online interviews. The participants represented a broad group of stakeholders including manufacturers, suppliers, distributors, integrators, cobot users, potential cobot users, and researchers.

Finally, the findings of the literature review and the interview study present a taxonomy of risks and harms related to cobot safety. The subsequent discussion highlights the challenges that industry faces as it exponentially grows in cobot usage, also in contexts outside of industrial and manufacturing settings.

Background

While industrial robots have been around for decades, only in recent years have we seen the rise of collaborative robots (cobots). Unlike conventional industrial robots, cobots are designed to be operated in a shared workspace with humans. Using new methods such as light-weight construction, rounded or padded corners, inbuilt force and/or torque sensing, or mechanical compliance, cobots are able to be utilised without the need for safety cages or active safety devices.

Cobots are an attractive proposition for small and medium enterprises (SMEs) as they lower the barriers for leveraging automation. Many cobots are designed to be user friendly and can be programmed by direct physical interaction, meaning they can be commissioned by existing staff with minimal training. The 'safe' nature of cobots means that systems can be used without the need for expensive and time-consuming safeguards. This facilitates agile utilisation of cobots which is important for SMEs that typically produce many variations of products in smaller production runs. Furthermore, cobots have comparably low cost compared to conventional industrial robots (Kopp et al., 2020).

Although cobots currently make up a relatively small proportion of the robotics industry (approximately 3% of robot sales), the cobot market size is expected to increase with sales of 34% by 2025 (Bi et al., 2021). In Australia, general adoption of robotics is low in part due to relatively small manufacturing and automotive sectors. To be competitive in global markets, and to address the needs of transferring some of the operations back to the country of origin due to the COVID-19 pandemic, Australian industries are likely to increase their adoption of robotics and particularly cobots (Ackerman, 2020).

However, much is unknown about the risks and harms of introducing cobots. Physical risks, such as impact, have been extensively studied and were paramount in the development of cobots. Less known are other forms of risk with regards to cobots, such as cognitive risks, emotional stress, socio-economic risks, and other human-related factors (Gualtieri et al., 2021). As the characteristics of collaborative robots are significantly different from those of traditional robots and other machines (ISO/TS 15066:2016), a definition of collaborative robotics is crucial to identify the health and safety implications in industrial settings. As the characteristics of collaborative robots are significantly different from those of traditional robots and other machines (ISO/TS 15066:2016), a definition of collaborative robotics is crucial to identify the health and safety implications in industrial settings. As the characteristics of collaborative robots are significantly different from those of traditional robots and other machines (ISO/TS 15066:2016), a definition of collaborative robotics is crucial to identify the health and safety implications in industrial settings. Unclear or vague terminology can lead to mistaken implications as it may not reflect the appropriate requirements (Vicentini, 2020).

According to the standards, a collaborative workspace is an "operating space where the robot system (including the work piece) and a human can perform tasks concurrently during production operation" (see Figure 1) (BSI Group, 2011, 2014; BSI Standards Publication, 2016). In this type of operations, "operators can work in close proximity to a robot system while power to the robot's actuators is available, and physical contact between an operator and the robot system can occur within a collaborative workspace" (ISO/TS 15066:2016). These technical specifications detail features and safety requirements for operating robots in different modes of collaboration. Collaborative robots are required to have the following features: safety-rated monitored step, hand guiding, speed and separation monitoring, and power and force limiting (10218-1:2011) (see Figure 2).

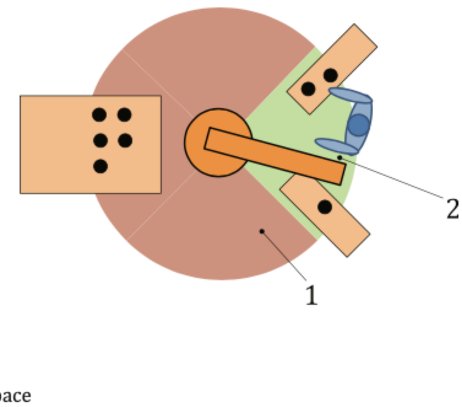


Figure 1 - Example of a collaborative workspace (ISO 15066:2016)

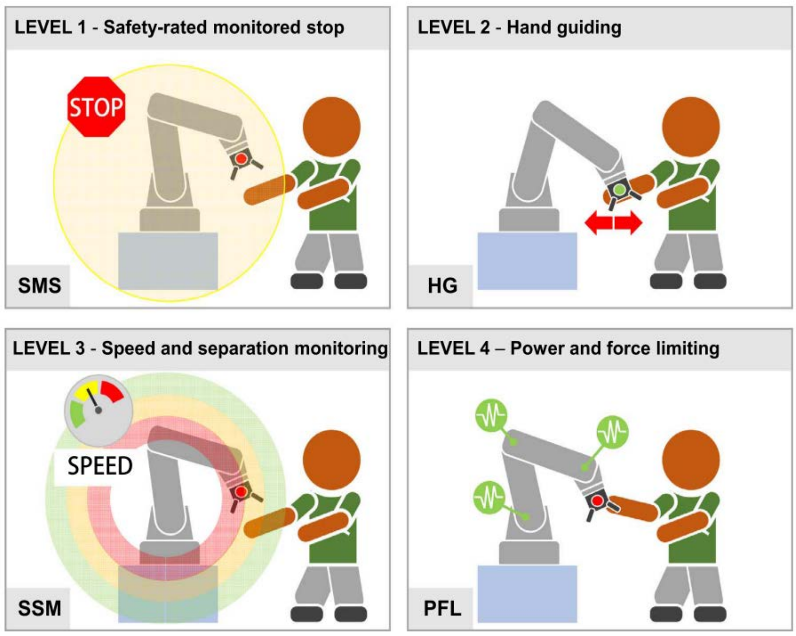


Figure 2 - Four safety modes as specified by the standards ISO 15066:2016, ISO10218-2:2011 (Villani et al., 2018)

In general, robotic systems allow for a wide variety of possible settings and operations. A robot can be considered as collaborative when; (a) it shares the workspace with a human, (b) tasks are performed at the same time and they can sometimes require physical contact, and (c) the robot's features include the four safety modes (see Figure 2) specified by the standards (ISO 15066:2016, ISO10218-2:2011). Figures 3 and 4 below illustrate the space in which robotic applications can fall into and highlight the distinction between industrial and collaborative robots.

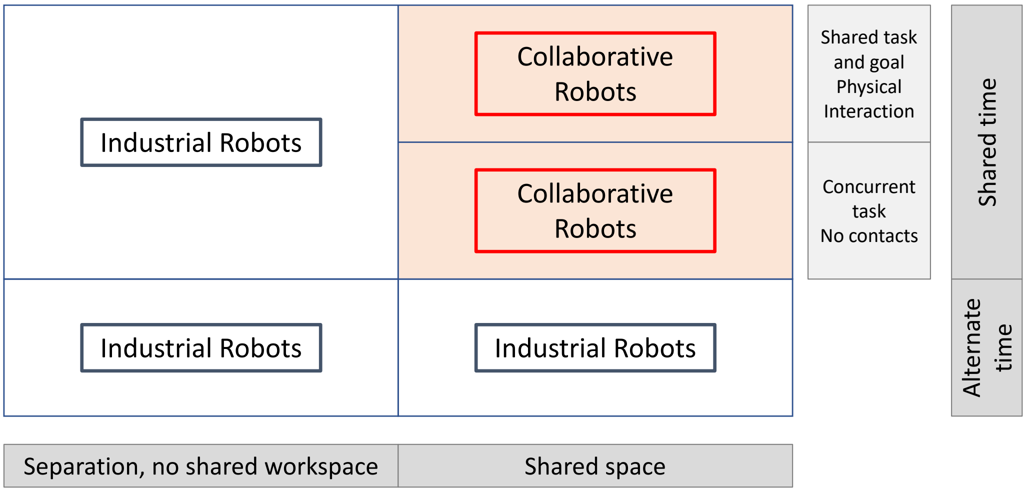
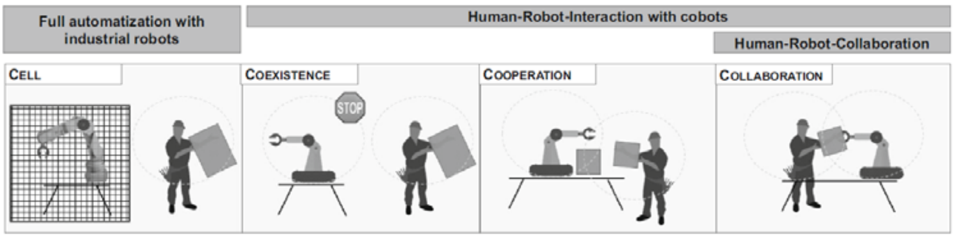


Figure 3 - Categorisation for collaborative robots (based on a framework by Vincentini (2020))



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 4 - Interaction types and characteristics of robots (Kopp et al., 2020)

This delineation from industrial robots calls for multiple dimensions when analysing cobot safety (see Figure 5). Not only the human operator and the cobot need to be taken into account individually, but also the working system or cell design as the collaborative space where human-robot-interaction takes place. In addition, enterprise and contextual factors play a role, such as processes, roles, responsibilities and training.

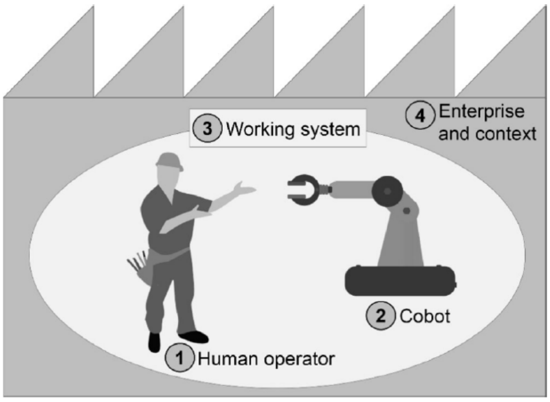


Figure 5 - Robot dimensions (Kopp et al., 2020)

The discussion section will investigate whether these definitions remained relevant outside of industrial and manufacturing contexts and assess whether this definition is consistent with research participants' understandings of cobots and human-robot collaboration. Alongside this, the interview study will explore whether these dimensions adequately capture a holistic perspective of the cobot system. In doing so, this will enable the study to identify gaps in the system that could potentially limit the adoption of comprehensive cobot safety practices.

Methods

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

Literature review

To gain a full perspective on the field of cobot safety, the literature review includes a broad variety of documents, from academic and grey literature sources, and employed a systematic review and horizon scan approach respectively. The goal is to:

I. Define a list of risks associated with the use of collaborative robots;
II. Identify existing tools that allow to measure, quantify, and assess risks for collaborative robots;
III. Identify case studies that provide meaningful examples of risk assessment and management; and
IV. Determine potential gaps between risks and harms and existing standards and guidelines.

The following sections illustrate the literature review methodologies used for the two type of sources (academic and grey).

Academic literature

The academic literature review was conducted by adopting a systematic approach to analyse existing research in the field. The approach used here to define the collection of relevant academic documents in informing the analysis follows established research practices (Levy & Ellis, 2006). The database and the search string were selected first. The database used for this work is Scopus, as it provides high quality scholarly literature, including documents from a variety of scientific fields. The search string was defined in accordance with the research aims and scope. Therefore, the selected search string is: *(cobot* OR "collaborative robot*" OR "human robot cooperation" OR "human robot collaboration" OR "human robot coexistence") AND ((safety W/2*[1] *(standard* OR guideline* OR requirement*)) OR (safety OR risk* OR hazard* OR "risk assessment"))*. Figure 6 illustrates the main components of the search string employed.

$$\begin{pmatrix} cobot* \\ \text{"collaborative robot* "} \\ \text{"human robot collaboration"} \\ \text{"human robot cooperation"} \\ \text{"human robot coexistence"} \end{pmatrix} AND \begin{pmatrix} safety\ W/2 \begin{pmatrix} standard* \\ guideline* \\ requirement* \end{pmatrix} \\ safety \\ risk* \\ hazard* \\ \text{"risk assessment"} \\ safe*W/2\ design \end{pmatrix}$$

Figure 6 - Search string used to identify risks in collaborative robotics

[1] W/2 is a proximity operator and indicates that the keywords are placed within 2 words apart.

Terminology is crucial to capture the collaborative context because as opposed to industrial robots, that are typically confined in a closed space, cobots require additional measures to ensure safety (Bi et al., 2021). As the project focuses on the risks related to cobots, the first part of the search string defines these systems using possible synonyms. Vicentini (2020) provided a structured overview of terms referring to collaborative robotics, as in some instances the terminology has been found to be inconsistent, particularly in relation to safety aspects. By following the terminologies presented in Figure 7, and in considering this project's cobot context, the terms under the upper right grey quadrants are used with the search string.

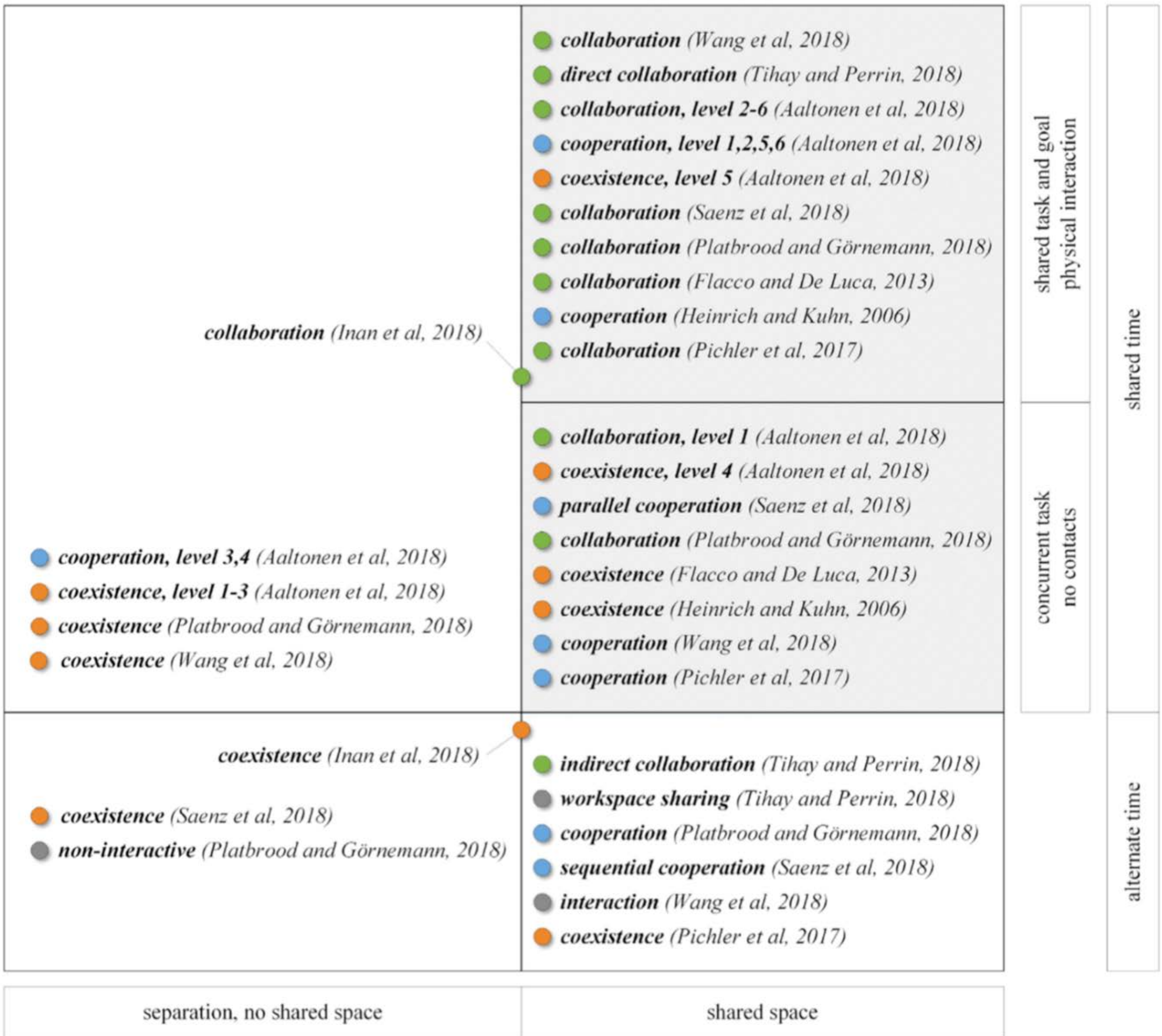


Figure 7 - Terminology for collaborative robotics (Vicentini, 2020)[2]

The search string returned 1,093 results[3] and of these, only journal articles, conference papers and reviews papers have been included in the final pool; resulting in a total of 1,018 initial documents. As the aim of the literature review is to analyse the most important and influential documents in the field, only the documents that have scored an average annual number of citations equal to 5 or above have been manually reviewed in detail, based on the criteria in Table 1.

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[2] The colours identify specific keywords (green: collaboration, blue: cooperation, orange: coexistence, grey: other)

[3] The Scopus search was carried out in August 2021 and includes all documents published until then.

Table 1 - Inclusion and exclusion criteria for the literature review

Inclusion criteria	Exclusion criteria
• The document lists risks and hazards in collaborative settings, • The document illustrates approaches for risk assessment in collaborative settings, OR • The document focuses on analysing, listing, or mapping risks arising from the use of collaborative robots	• The document does not specifically address risks, safety measures or risk assessment tools (e.g. briefly mention that a cobot application has some safety system embedded)

The total pool of documents (n = 1018) were analysed by drawing insights based on high level statistical analysis (presented in the quantitative analysis section). The most influential documents (n = 114) were then manually reviewed in order to analyse their content in detail and identify the main risks associated with collaborative robotics (presented in the qualitative analysis section). Figure 8 summarises the methodology used for the academic literature review.

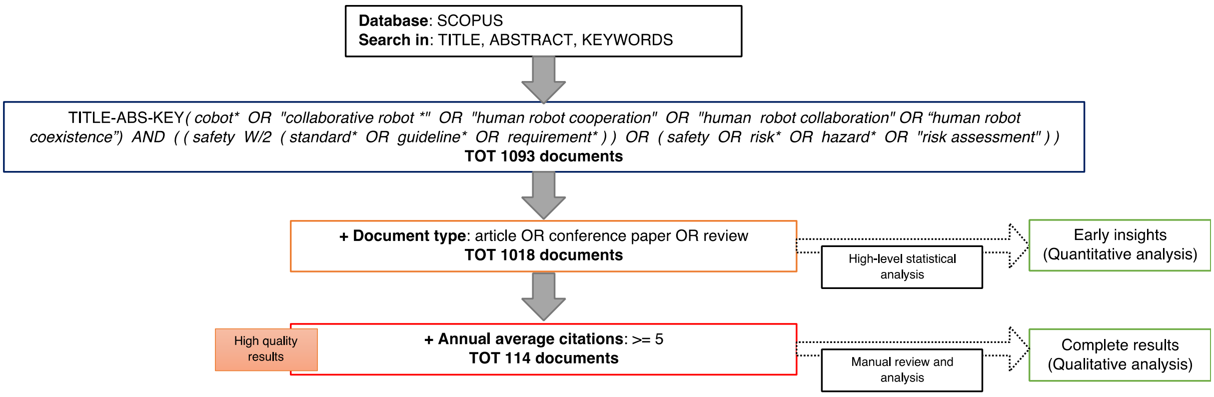

Figure 8 - Flow diagram of systematic review methodology

Grey literature

In addition to the systematic review of academic literature, relevant grey literature, industry standards and reports have been reviewed. This is conducted via a horizon scan approach to include articles referring to potential risks related to cobots (see Figure 9). For this reason, the same search string and key words displayed in Figure 3 have been used to identify relevant documents. The key words have been typed into the largest search engine, Google, and collected from 1st of January to 31st of December per year from 1996 to 2020. The search resulted in 26,400 documents. Next, documents were selected according to the priority of their type, publishing company and relevance; and then shortlisted (n = 50) based on the identified inclusion and exclusion criteria (see Table 1). Finally, a total of 24 documents have been assessed for identifying cobot related risks.

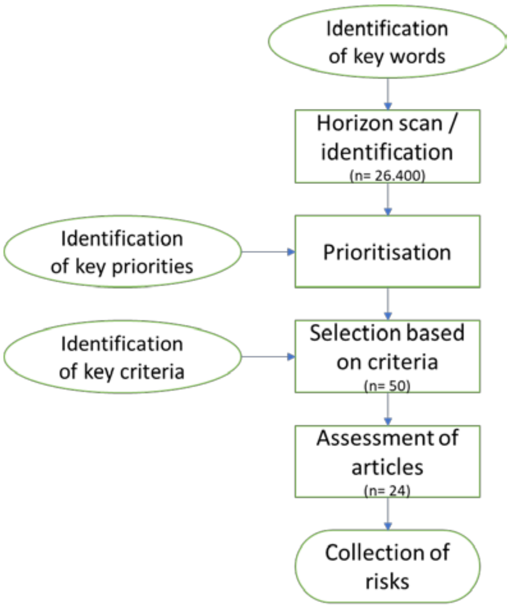

Figure 9 - Summary of the applied horizon scan approach

Interview study

The interview study employed the contextual enquiry methodology to conduct interviews with a sample of selected stakeholders to develop a holistic understanding of the work practices and behaviours within the cobot industry, and the potential risks and harms to workers operating cobots.

The purpose of this study was to:

I. Confirm and expand upon the literature review's identification of risks and harm;
II. Determine potential gaps relating to identified risks, the existing standards and guidelines;
III. Understand how cobots are being used in a variety of settings and the associated risks and harms;
IV. Explore the human factors that contribute to potential risks and harms; and
V. Investigate the socio-technical dimensions of the cobot system.

Recruitment strategy

The recruitment utilised a combination of purposive sampling and snowball recruitment strategies to capture a wide array of research participants. The inclusion criteria (Table 2) were intentionally broad to ensure inclusion of organisations and individuals, allowing representation of a diverse cross-section of participants and use-cases for cobots across industry sectors. Initially, 41 individuals from 28 organisations were identified as appropriate research participants and engaged via phone calls and a participation email (Appendix A). From this group, 15 people agreed to participate and were invited to one-hour individual online in-depth interviews. Nine of the 15 participants were engaged via recommendation from the research team and other research participants. Table 4 presents the breakdown of the participants according to sector and occupation.

Table 2- Inclusion and exclusion criteria for the interview study

Inclusion criteria	Exclusion criteria
• People currently working with cobots or robots who possess knowledge about the potential risks and safety implications. Organisations that are considering purchasing cobots.	• Participants who do not interact/operate with cobots or specifically address risks, safety measures or risk assessment tools.

During the recruitment process, research participants were asked to self-identify their interaction with the cobot industry using the following categories (Table 3): manufacturer, distributor, supplier, integrator, cobot user, potential cobot user, industry partner, and other.

Table 3 - 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 some implementation support.
Integrators	Companies that assist users in integrating cobots into workplaces and configuring software and hardware systems.
Cobot Users	Companies or individuals that have purchased and use cobots.
Potential Cobot Users	Companies or individuals interested in purchasing cobots in the future.
Industry Partners	Individuals who are associated in the development of cobot industry, including academic researchers.

Table 4 - Breakdown of research participants by sector and occupation.*

Interview	Interview participant category	Participant position title
1	Industry Partner	Researcher
2	Industry Partner	Researcher
3	Supplier	Business Development Manager
4	Supplier and Integrator	Director
5	Cobot User and Integrator	Technical Officer and Managing Director
6	Supplier and Distributor	Project Engineer
7	Manufacturer and Distributor	Service Manager
8	Cobot User and Purchaser	Founder
9	Cobot User	Robotic Facilitator
10	Industry Partner	Researcher
11	Cobot User	Technical Officer
12	Potential Cobot User	CEO
13	Cobot User	General Manager
14	Manufacturer and Distributor	Sales Engineer
	Manufacturer and Distributor	Sales Manager

Interview procedure

In total, the qualitative study included 15 research participants across 14 semi-structured interviews (one interview included two research participants) for approximately one hour. Due to COVID-19 restrictions, the interviews were conducted online using Microsoft Teams and loosely followed the sample interview questions guide (Appendix B). The project was conducted with ethical approval (UTS HREC REF NO. ETH21-6244). Data collection commenced on the 19th of August 2021. At the beginning of each interview, participants were asked whether they would like to provide consent to being interviewed and recorded for note-taking and transcription purposes. All research participants consented for their interviews to be recorded for note-taking and transcription purposes.

The interview questions were developed to validate and complement the findings of the literature review through the lens of the participants. This ensured that the research could capture a comprehensive image of potential risks and harms. It should be noted that interview responses referenced in this report have been lightly edited for concision and readability.

Synthesis

The recorded interviews were uploaded to the online transcription and coding platform 'Condens'. Two members of the project team read the transcriptions and coded the findings based on the insights of the literature review. Other key areas of concern emerged including unclear cobot definition, risks specific to end effectors, task assignment, and guideline/recommendations. The tag categories can be seen below.

- Physical Risks – 324 tags
- Psychosocial/Ergonomic Risks – 102 tags
- Ethical Risks – 144 tags
- Cobot Definition* - 41 tags
- End Effector* - 13 tags (however end effector risks were also tagged as physical risks)
- Guideline/Recommendations* - 44 tags
- Roles and Responsibilities* - 62 tags
- Task Assignment* - 100 tags
- Training* - 14 tags

** These tags were created to identify emerging patterns in the interview study and were used to highlight gaps in the literature search.*

Once the qualitative data was categorised and tagged, the emerging patterns and themes were synthesised. Gaps in in the literature relating to real-world applications of cobots across diverse work settings were also identified and will be explored in the discussion section.

Methodological limitations and ethical considerations

Participants were understandably concerned about disclosing incidents or risks and harms that they had personally observed in fear that they would implicate themselves and their organisation. To ensure that the interview space remained comfortable and safe, participants were asked generalised questions about risks and harms they had observed from colleagues and across the industry. Additionally, participants were reminded that their names and workplaces would be anonymised and any data collected would be confidential and only shared with members of the interview study team.

Due to COVID-19 lockdown restrictions, the planned observational site visits could not be completed in time for this report. As noted above, as many participants were apprehensive to speak to their personal experiences with cobots; the observational site visit may have been beneficial in drawing greater insight into risks and harms that could be typically overlooked. The observational site visits will be conducted at a later stage of this research project.

In using a snowball recruitment strategy, the interview study experienced an oversaturation of research participants with a stronger disposition to accept cobots and the future possibilities for this industry and technology. Although the research team engaged with several cobot users companies, only one operator working in advanced manufacturing was interviewed. This participant was recommended by several other research participants and was seen as an exemplar case study for the future of human-robot collaboration in Australian manufacturing. This is not reflective of the wider experiences of operators using cobots. In later stages of this research, it would be beneficial to engage with more operators and WHS advisors to provide a more comprehensive understanding of the behaviours and attitudes of cobot users.

Findings

Quantitative analysis: Literature review

The literature review provided important insights into existing trends and risks concerning cobot safety. The following sections provide early insights around research interest in cobot and development of publications over time, the countries and institutions contributing to the field, and the main subject areas from which the studies originate.

Development of the cobot field over time

The academic research interest in risks and safety of collaborative robots has developed significantly over the last decade, especially over the last five years (see Figure 10). Cobot related standards and grey literature had been available for several years. Safety standards including countermeasures for specific machines have been released in 2011 through ISO 10218-1 and ISO 10218-2. Technical specifications for collaborative robots have been defined through ISO TS 15066 later in 2016. Despite the existence of these pioneering documents, grey literature and academic research in the field has drastically increased since 2016.

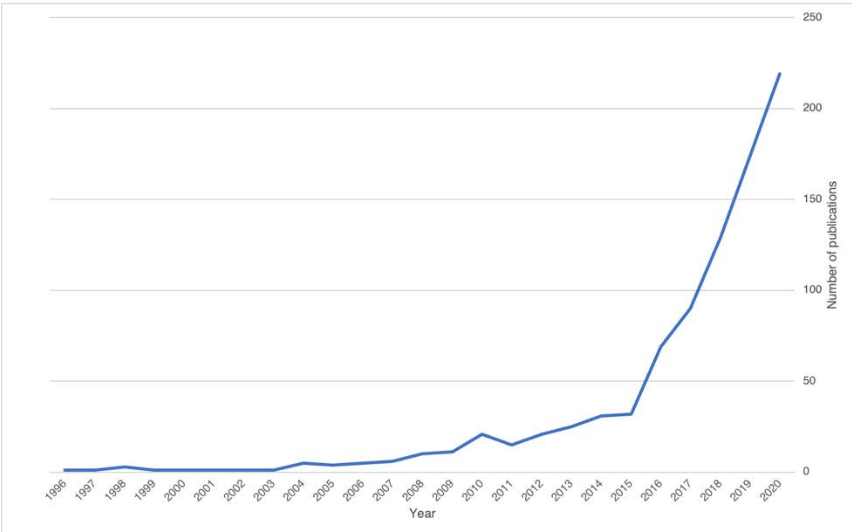

Figure 10 - Development of academic publications on cobots over time

Figure 11 provides an overview of the development of Google search results. The numbers of results include all kinds of search results, not limited to grey literature articles. The first year of collection, 1996, shows only 3 results, while over the last decade, a revealing trend of exponential growth in attention, with 7590 results in 2020, can be examined. Interestingly, the development of the number of Google search results is analogous to the academic literature results.

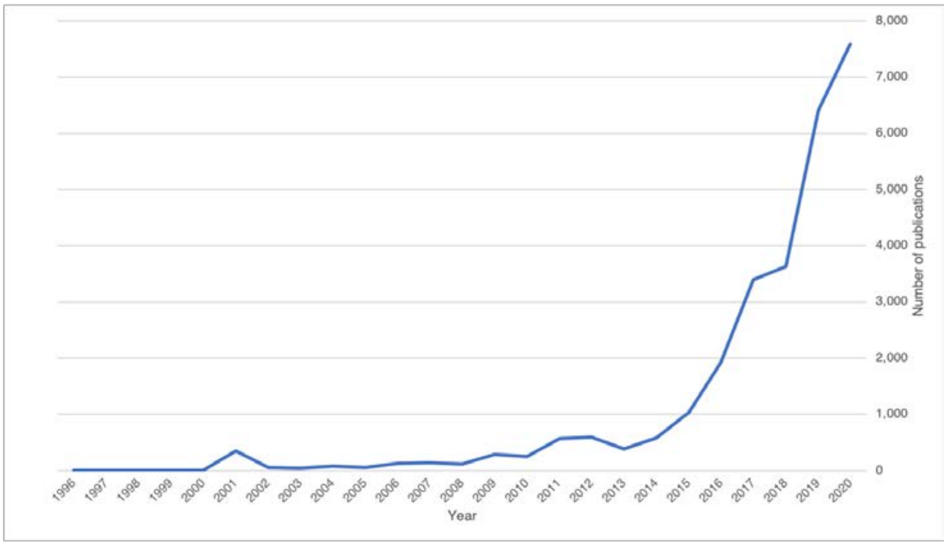

Figure 11 - Development of Google search results between 1996 and 2020

Subject areas within the field

Academic contributions come from a variety of subject areas, highlighting the interdisciplinary nature of the cobot research and application (see Figure 12). Not surprisingly, most of the results come from engineering (37.8%), computer science (33.6%), and mathematics (10.9%). Interestingly, social sciences are the next major contributor (2.8%), including 54 publications.

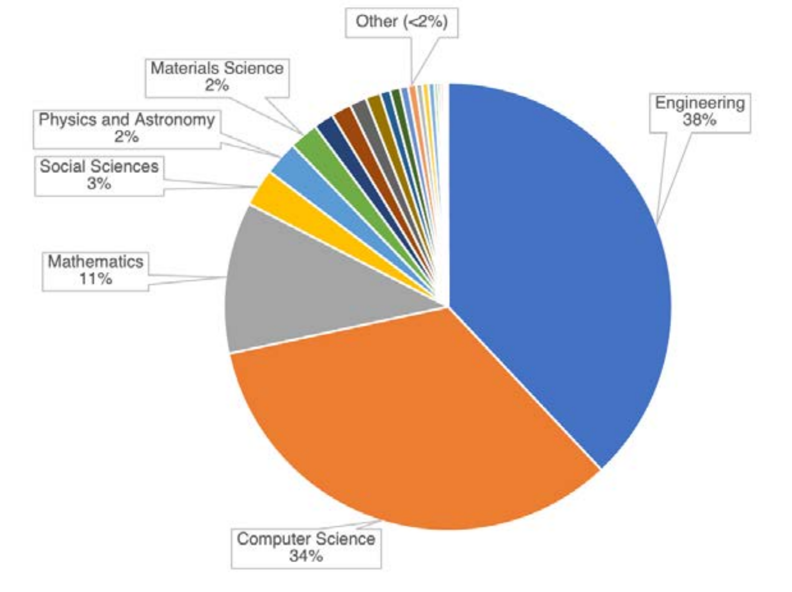

Figure 12 - Subject areas contributing to the search outcome

Even more remarkably, the evolution over time of academic publications within social sciences has spiked since 2016 (see Figure 13), thus supporting the possibility that existing standards may not address risks from all perspectives necessary. This suggests an increasing interest for social aspects to be included in safety guidelines for collaborative robots and will be further discussed in the following sections.

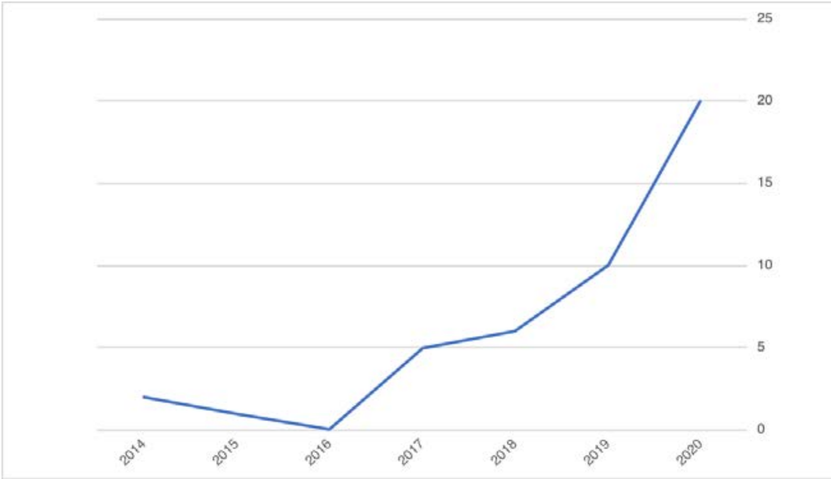

Figure 13 - Evolution of publications in social sciences over time

Qualitative analysis: Literature review and interviews

This section presents three main findings that have emerged from the in-depth qualitative analysis of academic literature, grey literature, and the interviews:

- Finding 1: risks and harms related to human-robot collaboration according to the three major categories identified from the literature: physical, psychological, and ethical.
- Finding 2: existing indices and models that help in quantifying risks as a basis for mitigation.
- Finding 3: the need for a holistic approach towards risks and harms and a showcase of mitigation strategies, demonstrated through selected applications (i.e. case studies).

The following sections provide a comprehensive structure that allows the main risks and harms to be presented with possible quantification and assessment. The findings highlight risks and harms that occur even when proper integration, best practices and standards are appropriately followed.

Finding 1: Risks and harms related to human-robot collaboration

Risks are the possibility of negative events that can occur with a certain probability induced by unplanned circumstances. Risks are triggered by a certain cause and result in negative consequences. In an industrial setting, human health and safety shall always have the highest priority over machines. Existing literature mentions numerous challenges related to the safe and effective use of cobots. In this context, all studies mention physical harm as a consequence related to the use of cobots. Additionally, an increasing portion of the literature also emphasises psychological and ethical harm.

The following section presents latest research insights regarding risks and harms, summarised in Table 6 . The three main categories physical, psychological and ethical have been defined based on the type of harm that the risks can cause for workers. Additional risks identified in the interview study are marked with an asterisk (*). Each main risk, its consequence and potential causes are discussed below. This section will not cover the relation between the probability and the impact of the risk occurrence, even though this is indispensable consideration when it comes to the organisation of risk measures.

Table 5 - Summary of risks and harms related to human-robot collaboration

Harm	Risk	Description
Physical	Hazardous collisions	As robot and humans share the same space, non-functional or unwanted contacts may occur.
	Cybersecurity	Cyber-attacks may cause robots to move unpredictably and harm the human.
	Lack of focus	When the human 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 potentially causes physical harm to humans.
	Debris*	The debris generated by some collaborative tasks may harm humans.
	Pinch points*	During task operation humans and/or materials and objects may 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 stress or extra work for humans.
Ethical	Social environment	As opposed to regular settings in which humans 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, which influences the level of acceptance.
	Data collection*	User data may be collected, used, and sold without user consent.

**Additional risks identified in the interview study are marked with an asterisk (*)*

Physical risks and harm

Physical risks are mainly represented by collision events involving a human and can occur due to a variety of reasons leading to unexpected behaviours of the cobot. Human health shall always have the highest priority when it comes to human-robot collaboration and should always be protected, and as a result physical risks receive particular attention in the implementation of cobots. The literature and interview study offers a wide spectrum of potential causes for physical risks, which have been extracted and clustered (see Table 7).

Table 6 – Potential causes for physical risks

Physical risk	Potential causes for physical risks	Description
Hazardous collisions, loss of movement control, debris, pinch points	Inappropriate implementation and application (inadequate lighting, positioning, process integration)	The inappropriate implementation of human-robot-collaboration (i.e. due to bad lighting of work space, wrong position of cobot or human, or inadequate process), leads to inappropriate application, which may ultimately result in physical harm of human or damaged components of the cobot system.
	Component malfunction	Mechanical components of the system breaking or loosening increase the risk of physical harm.
	Malfunctioning safety measures	The malfunctioning of safety measures may expose humans to increased physical risks and potential damage to the cobot system. Examples include power or force limiting not working, uncoordinated safety solutions between multiple involved cobots, lacking functional security.
	Bypassing safety measures*	Safety measures may be ignored, bypassed, or turned off by cobot users to continue operation or troubleshoot issues. Factors such as scaling fences, or turning off safety sensors, increase the risk of physical injuries.
Hazardous collisions, Loss of movement control	Electrical hazard	Electrical hazards, such as confusion with voltages within a system, broken or disconnected electrical connectors, loss of variation of power, human contact with electrical connectors, may cause physical harm to the user or damage components of the cobot system.
Hazardous collisions, lack of focus	Noise induced hazard	Very high noise level may distract humans, drown warning signals, prevent humans from conducting their activities or even cause the loss of balance within the working area, which can cause physical harm to humans.
Hazardous collisions, debris	Chemical hazard	The exposure to chemicals, such as creation of fumes, explosive atmosphere, or extreme temperature, can physically harm humans.
Hazardous collisions, cybersecurity, lack of focus, loss of movement control, debris, pinch points	Insufficient safety measures	The lack of safety measures such as inadequate training, not covering certain hazardous areas, inadequate safety limits (speed or distance related), or insufficient testing of tasks, expose humans to increased physical risks.
	Systemic malfunction	Malfunctions including force transients, inhomogeneous interfaces, or system failure can follow, increase the risk of physical harm to the humans or damage to the cobot system.
	End effector*	Specific physical risks relate to specific end effectors or end-of-arm tooling. Examples include burn risk generated by welding or hazardous chemicals, cuts generated by sharp blades. Other risks may be generated by the installation industrial robot end effectors to cobots, or the ad-hoc installation of conventional tools that cannot be turned off with emergency stops or dead man switches.
	Human error*	Human mistakes such forgetfulness, assuming cobot has 'common sense', incorrectly attaching end effectors, or peripherals may trigger events that cause physical harm to humans.
	End user customisation*	Cobot users customising a cobot/setting/end effector/application without conducting appropriate testing or risk assessments increases the likelihood of physical risks. This also includes ad-hoc solutions such as zip-tied power drills to end effectors.

	Over-estimating safety measures*	The fact that users often have assumptions that a cobot inherently has 'common sense' that will prevent it from causing harm during operation or when implementing non-collaborative applications, can expose them to increased physical risks.
	Difficult interaction mechanisms*	Limited knowledge of programming may result in users guessing how to operate cobot actions (mistake repetition, troubleshooting errors, incorrect programming for action), which results in increased exposure to physical risks.
Hazardous collisions, Cybersecurity loss of movement control debris pinch points	Cybersecurity	Despite being a risk consequence itself, cybersecurity can also be a cause for physical risks, such as Cobots being manipulated to cause physical damage.
Hazardous collisions, loss of movement control debris pinch points	Loss of movement control	Despite being a risk consequence itself, loss of movement control can also be a cause for physical risks such as loss of control or unexpected movements that can cause physical damage.
	Inadequate testing*	Task assignments that have not been appropriately tested through approaches including simulation, prototyping, or testing kits, lead to increased physical risks.

**Additional risks identified in the interview study are marked with an asterisk (*)*

Hazardous collisions

The most common theme across literature refers to risks related to potential collisions, caused by humans and robots sharing the same space in order to collaborate. This type of workplace can potentially put operators in dangerous situations that can ultimately cause injuries (Vasconez et al., 2019). According to a review by Gualtieri et al. (2021), the most developed theme in the field of safety for collaborative robots is physical safety, including contact avoidance, contact detection and safety.

Impact of sensors on hazardous collisions

Research participants clearly understood the importance of these safety measures in preventing hazardous collision. However, it was noted that malfunctioning safety measures such as damaged sensors were difficult to identify and assess. While cobots have their own internal diagnostics, one user claimed that they were unable to perform manual checks to assess if the safety sensors were working "*because the sensors are embedded within the machine itself*". The lack of access to safety measures can prevent users from performing routine risk assessments and safety checks on cobots. Intentionally damaging sensors was also disclosed as a method to sabotage cobot integration. One research participant disclosed that they had heard of operators cleaning cobots with caustic solutions and abrasively handling the cobots. The topic of sabotage will be explored later in this section.

Mobile cobots and the risk of hazardous collisions

A key selling point for cobots is that they are lighter and smaller compared to Industrial Robots, making them easier to move and transport. The interviews identified a multitude of ways end users installed cobots upon mobile equipment such as trolleys, Automated Guided Vehicles

(AGVs), Autonomous Mobile Robots (AMRs), and conveyor belts. Once a cobot is installed on mobile equipment, the work cell becomes dynamic and not clearly defined. Dynamically changing work settings for cobots were identified by researchers as a potential area for improvement in the design of cobots. It was noted that mobile cobots pose a *"different species of problems"* to fixed cobots arms. In dynamically changing work cells, cobots face the risk of colliding with workers who share the same space but are not the main worker supervising a cobot. One cobot researcher that was interviewed, noted collisions can result in workers being *"….run over by those things [AGVs] and they can sort of break your ankle"*.

One way that end users have addressed this risk is by programming strict boundaries that prevent cobots from operating outside of the edge of their mobile platform. Multiple research participants noted that it was possible for someone to accidentally lean across boundaries and collide with a cobot or its end effector. This was more likely to occur with users who were less familiar with cobots. For end users who transported a cobot to a variety of settings, the greatest potential for collision was in the initial set-up. They explained that during set-up safety measures and sensors are either turned off or require reconfiguration and recalibration for the new setting. This stresses the importance of considering the dimension of workspace and/or cell design in minimise the potential risk of hazardous collisions.

Ergonomics

In general, collaborative robots can potentially improve working conditions for operators by providing several benefits including improved ergonomics - the reduction of physical and mental loading. For example, in a collaborative assembly scenario, cobots reduce the risk of strain injuries due to the lower physical effort (Cherubini et al., 2016). As cobots interact with humans, ergonomic factors still need to be taken into consideration. In interviews with end users, the range of motion at *"which a robot could move most like a human"* was a strong consideration for end users operating in the medical industry. One user working in the patient physical rehabilitation setting noted that the kinematic model was an important inclusion for cobots attached to patients. Currently, standards related to ergonomics in collaborative settings do not exist (Bi et al., 2021). Interestingly, the standards (i.e. DIN EN ISO 14738 and VDI 3657) specify ergonomic and anthropometric requirements for operators (Faber et al., 2015). Therefore, regardless of the type of robot, factors such as the dimension of the workplace, and the setup of appliances, boxes and tools should meet ergonomic requirements.

Operators may prefer how they like to setup their workspace for collaborative use. These configurations are important to ensure collaborative operation is ergonomic; it also highlights a potential cause of physical harm. When cobots are shared by several operators, users may begin operation without assessing whether a cobot is correctly calibrated for their task. This may result in hazardous collisions or unexpected movements.

While cobots offer the potential for improved ergonomics, the collaborative setting raises the risk of physical injuries due to the proximity with robots. In the context of physical hazards, the existing standards (ISO 10218-1, ISO 10218-2, ISO/TS A15066) require four safety mechanisms (see Table 8). Although the guidelines specify how to respond to general physical hazards, they cannot predict all possible risks associated with a specific collaborative scenario. The standards do not specify when these safety actions need to be in place within a specific scenario. The risks need to be defined and evaluated on a case-by-case basis through a risk assessment.

Table 7 - Collaborative operative modes (Michalos et al., 2018; Villani et al., 2018)

Safety measure	Description
Safety-rated monitored step (SMS)	Human and robot can work inside the collaborative area but not at the same time. When the operator is in the shared space the robot stops.
Hand guiding (HG)	Humans get in touch with the robot directly to instruct positions through a guiding device that guides the robot motion. For this scenario the robot needs to be equipped with SMS and SSM.
Speed and separation monitoring (SSM)	Human and robot can operate in the share space at the same time thanks to safety sensors. These divide the space into three areas. In the green zone the robot operates in full speed, reduced in the yellow zone, and it stops in the red one.
Power and force limiting (PFL)	Limiting the motor power and force so that human and robot can work together in a shared space. No threshold for protective distance is in place and contact may occur.

End effector

The interview study identified a broad range of harms that can only occur with specific end effectors and end-of-arm tooling. An end effector is a device or tool that can be attached the end of a cobot arm that enables it to interact with its environment. One integrator explained the importance of end effectors to the cobot system as a cobot without an end effector would be like *"having your hand cut off at the wrist"*.

The interview study captured a diversity of cobot applications that fashion non-cobot tools to work with end effectors, examples included hot-wires, pneumatic drills, linishers, laundry folding, and even making pancakes. Furthermore, many of these tasks have been developed ad-hoc by cobot users without risk assessments or consultation with integrators. A strong example was highlighted in the interview study where a cobot user attached a drill to the end effector using plastic zip ties. Upon reflection the research participant realised that this was hazardous as they would have been unable to immediately turn off the drill if something had gone wrong. Alongside this, suppliers had observed that their customers will purchase industrial robot end effectors such as air-actuated grippers for cobots. The supplier explained that *"If you put your finger in one of these grippers, it was gonna hurt"*. The primary reason that users would customise tools and use industrial end effectors was cost; purchasing cobot specific tooling is often expensive.

While this type of end-user customisation points to an exciting future for cobots, there are simply too many unique risks and harms associated with each of these tools and tasks that this report can comprehensively capture. It is apparent that for end users to consider the potential harms when using end effectors, they must understand when cobots are being used in a non-collaborative manner. Inappropriate application will be explored later in this report.

End effectors were often reported as missing sufficient safety measures such as sensors installed onto them. This is especially important considering that safety sensors are one of the main ways that cobots prevent physical harm and collisions. Furthermore, research participants highlighted that when testing applications using simulation software, end effectors were simulated as static objects. This limits users from identifying errors or issues that may cause physical risks before a full operational run.

Cybersecurity

In the context of advanced manufacturing systems, where devices and machines are interconnected, safety often relates to security, as the system could be vulnerable to cyber-attacks that induce unwanted behaviours (Bi et al., 2021; Robla-Gomez et al., 2017). Collaborative cyber-physical systems include a variety of features, including hardware, sensor network, and information and communication technologies. This allows to connect these systems to their intra- or internet, thus exposing them to security risks (Khalid et al., 2018). As a result, security and safety aspects become strictly related. Grey literature offers a spectrum of causes for cybersecurity risks, mentioning inadequate safety validations or considerations allowing unauthorized access and sabotage; technological causes such as manipulated control components; malware infiltrated through hardware, inter- or intranet; or even limited accessibility for an intended use.

Sabotage

Like the cybersecurity risk of unauthorised access and manipulation, human operators can also place a risk of sabotage. In interviews, an integrator stated that it was a relatively common occurrence to hear of operators sabotaging cobot systems as they saw it as a threat to their livelihood. The integrator explained that sabotaging cobot systems could be a relatively easy task that would not require any programming or technical knowledge.

> *"You can just go to the teach pendant and just delete a few lines here and there, you wouldn't really need to know what those lines even meant". – Integrator.*

While cybersecurity is a standalone physical risk, cybersecurity can also cause other risks such as hazardous collisions. The integrator shared various examples of how operators in the past had changed programming to encourage collision.

> *"…They've purposely gone in and sort of tried to change the robot code so it crashes into something on purpose, jammed up a conveyor or destroy sensors installed…" – Integrator.*

The integrator further emphasised how easy this is by stating;

> *"you can just delete a line that checks this specific input, and obviously it will no longer check that input, skip over it and crash into something else".*

Cybersecurity is a risk mentioned in academic and grey literature. The review did not find extensive reference to cybersecurity, which could be explained by the low probability of their occurrence. A hazardous collision is more likely to occur than a cyber-attack. Nonetheless, the potential impact that a cyber-attack can have is wider as it happens on a systemic level. Cyber-attacks can affect many robotic systems or entire manufacturing sites at once, while in most cases, a hazardous collision affects a single operator.

Loss of movement control

When the cobot moves unexpectedly and cannot be controlled anymore, the consequence could lead to physical harm to the operator. The loss of movement control of a cobot system can have different causes, such as component failure; malfunctioning safety measures or control mechanisms; e.g. due to force transients, inappropriate implementation, cyberhacks, or wrong application by human.

To create safe collaborative environments, cobots are intentionally limited to slower movement speeds and lower payloads to minimise the severity of hazardous collisions. When cobots reach their maximum payload, end users and integrators noted that performance was inconsistent and unreliable. One integrator observed that once cobots reach their max payload they tend to *"jitter a little bit, as if it's moving on its own and it gets really slow"*. When cobots are a part of a larger, more complex system, these unreliable speeds and unexpected movements can impact entire work processes.

Unexpected movements can also result in hazardous collisions with users and in the workspace. One user disclosed an incident where their cobot punched through a Perspex screen due to the cobot taking an unexpected path that collided with the surrounding workspace. This is most notably caused by users expecting a cobot to move in a predictable human-like manner or behave with 'common sense'. When a cobot needs to move from A to B, regardless of whether the two points are physically close to each other, cobots can sometimes take roundabout paths to reach the destination. This issue was a primary concern for an end user who trains students to use cobots; they remarked that they remind students that *"it's still a robot and they need to move out of the way, especially when they're running things for the first time"*. A clear recommendation for this risk is to test task applications using simulations and tiered testing protocols. However, users rarely tested task applications prior to a full operational run.

Although software updates are helpful in protecting cobot systems against cyberattacks, they can also pose their own risks. Interestingly, integrators and users commented that cobot software updates were typically avoided unless necessary to continue operation as they often reset calibration points. One user shared an experience where the robot manufacturer had upgraded their software and reset the calibration points without alerting the user of any changes. This resulted in a loss of movement control and a tedious and time-consuming process of recalibrating the cobot for the task. Interestingly, a cobot distributor stressed that firmware updates would notify users if they needed to recalibrate their machine; this suggests that there is variance in what cobot users are notified of across different cobot models.

<u>Debris</u>

There are two main types of risk associated with debris that need to be considered, debris caused by (1) task application, and (2) unexpected movement.

Debris caused by task application

The first case is debris created by the task at hand (e.g. metalwork, linishing). This form of debris can cause unsafe working conditions and injuries for humans including but not limited to; poor ventilation, tripping & slipping hazards, fires, chemical burns, and spills.

For these tasks, debris is a natural by-product of the task. This requires organisations to consider non-cobot related risk mitigation strategies to safely manage debris. Integrators can overlook the potential risks associated with task-specific risks when they don't consult workers with specialist knowledge (e.g. welders) during the implementation process of the task. This highlights a gap in testing protocols as many integrators and end-users solely rely upon simulations to test the task application as these programs are unable to simulate how and where debris will travel. Debris and dust created by task applications may also accumulate in the open joints of a cobot arm, causing component deterioration. Another common form of debris mentioned by a supplier was the risk of cobots accidentally spilling the contents of a container or a box breaking while a cobot is carrying it.

Debris caused by unexpected movement

The second risk with debris is related to unexpected movements from the cobot. Unexpected movements may result in an object being thrown across the workspace. The case for physical barriers for Industrial Robots is two-fold; they safeguard workers from accidental collision and prevent objects from being thrown out of the robots assigned space. Safety measures for cobots such as light curtains prevent workers from entering hazardous spaces but do not prevent cobots from throwing objects across workspaces. Therefore, the design of the workplace/cell becomes a critical consideration for minimising the risks and harms created by debris.

> *"In theory, it could throw a heavy object across a factory... People have been saying, well, you can replace physical barriers with laser trips and that stops people walking in because as they walk in, it shuts everything down. But it doesn't stop objects being hurled across the factory." – Interviewed researcher*

Pinch points

Pinch points occur when a human or other material can be caught between the joints of a machine. There is an increased risk of users being injured by being caught in a pinch point when they are working in close proximity to cobots such as hand-guided operations. A participant noted that the materials and physical design of conventional cobots do not adequately address these pinch points. For users inpatient rehabilitation, pinch points were seen to be the most common injury. An integrator noted that historically, testing kits would include fake fingers that could be used to measure severity and minimise the risk of pinch points. However, they remarked that this had recently become less common and highlighted that fake fingers were not a standard requirement for risk assessments.

Lack of focus

If an operator lacks concentration and focus, tasks may not be fulfilled as intended which can lead to the cobot causing physical harm. The lack of focus can be of human nature, due to an inadequately prepared operator. An example of this type of human error was noted in an interview with an end user who had accidentally forgotten to turn off the cobot they were using and observed it drifting across the workspace. Lack of focus may also be externally induced, due to factors such as complicated or unclear interactions (Michalos et al., 2018), inadequately prepared working areas (Sauppé & Mutlu, 2015), or a combination of those.

Psychological risks and harm

Psychological risks emerged from the literature and interview study. In this context, operator risk is not limited to physical hazards, but also includes the operator's psychological state. Cognitive ergonomics or human factors include all aspects related to the psychological safety of operators (Djuric et al., 2016; Maurtua et al., 2017). Cognitive ergonomics is a novel field but is gaining increasing interest. At present, in the area of safety for collaborative robotics, one third of academic studies relates to cognitive ergonomics, while the remainder focuses on physical concerns (Gualtieri et al., 2021). Table 9 offers an overview of potential causes for psychological risks, identified through grey literature. Research participants were noticeably ambivalent to share psychological risks and harm; this will be explored further in this report.

Table 8 - Potential causes for psychological risks

Potential causes for psychological risks	Description
Unfamiliar robot morphology	An unfamiliar robot appearance can negatively affect operators' perception and contribute to a sense of insecurity and discomfort. If familiar design elements including overall form and eyes are missing, operators may feel uncomfortable and insecure when working next to them (Sauppé & Mutlu, 2015), which affects the psychological state of the operator.
Inappropriate process implementation	If the processual work of human-robot-collaboration is implemented poorly, i.e. due to overworked operators or poorly arranged collaboration between various cobot-human interactions it can result in psychological risks for operators.
Insufficient safety measures	If safety measures are insufficient to ensure a safe working environment, e.g. due to insufficient training or inadequate safety limits (e.g. speed or distance related) it can cause psychological harm in form of stress to the operator.
Job precarity*	Cobots replacing or changing a workers job.

**Additional risks identified in the interview study are marked with an asterisk (*)*

Lack of trust and stress

Trust has become an important factor to consider (Djuric et al., 2016; Maurtua et al., 2017). Maurtua et al. (2017) proposed a study in which they conducted experiments to assess the opinion of workers in regard to the interaction mechanisms and safety. The experiments involved different tasks and the workers' feedback has been collected through questionnaires. Results revealed positive levels of trust, along with the widespread opinion that cobots will help reduce the number of demanding tasks and ultimately increase productivity.

In the interview study the primary contributor for stress and lack of trust was the perceived risk of job loss for workers. Those interviewed from a sales backgrounds typically underplayed the severity of this risk, stressing that cobots would only replace unwanted *"dirty, dangerous, and repetitive"* jobs. However, in interviews with users it was unclear whether this claim was entirely accurate. One operator explained that although cobots had made their work less dangerous they also claimed that the process of programming a cobot task was repetitive and tedious. that working with a cobot can be repetitive and tedious. Furthermore, a supplier explained *"…in the industry we used to try to tell people that we don't take jobs, but we do take people's jobs… we may take some people's job but we actually save the company"*. This indicates that the fears of job displacement have not been as strongly considered as other facets of worker health and safety. As previously mentioned, this fear and stress caused by job precarity can result in workers sabotaging cobots.

Mental strain
When operating cobots, operators must feel comfortable, and the mental strain associated with tasks has to be bearable. Speed, distance and warnings of motions directly influence the psychological state of operators (Robla-Gomez et al., 2017). When these safety measures are overridden to increase productivity, it directly impacts an operator's sense of comfort when using the machine. The interview study highlighted how speed and the payload assigned to cobots made even well-versed users nervous to work collaboratively with the cobot. Unpredictable motions of the robot can cause unpleasant reactions such as fear, shock, or surprise. Furthermore, the anticipation of the potential for unexpected movements and collision reportedly made users nervous. Recent research has been increasingly focusing on these aspects. For example, to increase the level of comfort, some research has focused on the ability of cobots to read human emotions. Some of the technologies used to increase the ability to read human emotions include human behaviour pattern recognition and on-skin sensors (Murashov et al., 2016). These measures were not mentioned by research participants in the interview study. In general, more recent applications adopt a holistic approach that takes into consideration a wider range of risks, including the psychological state of operators. For example, the European Union (EU) funded ROBO-PARTNER project has among their targets to decrease the ergonomic impact, both physical and cognitive, as well as increasing the feeling of comfort and acceptance by human operators (Michalos et al., 2018).

Collaborative settings that require repetitive and tedious actions may make operators feel fatigued, tired, or bored, further contributing to a lack of focus and concentration on the task at hand. It was noted that many users felt calibrating cobot for tasks was time-consuming and frustrating, despite claiming that hand-guided operation was comfortable and easy to use. In settings where users supervised operators who were less familiar with cobots, for example, in educational environments, the users noted that the focused attention required for supervision was tiring and draining. Furthermore, one user who managed cobot operators shared that operators were unlikely to disclose when they felt fatigued as they were concerned that it would indicate lesser performance or lesser capability as an operator.

The typical duration of collaboration appeared to fluctuate depending on the task and setting, with some users restricting interaction to 30 minutes or less while others worked for several hours. The study was unable to identify whether a standard exists to outline the maximum duration for user operation.

Complicated interaction mechanisms

Complicated interaction mechanisms can have a negative impact on situation awareness, highlighting the relevance of clear interaction mechanisms. When one user described working with a cobot as though it is *"like driving a car from outside",* a strenuous task that can impact situational awareness. Due to factors such as unclear interaction mechanisms, the operator could have doubts and concerns about the anticipated moves of the robot (Michalos et al., 2018). Thus, the operator may not be able to identify problems and may take incorrect or unnecessary actions, which can increase the severity of harm. A common complaint by integrators was that operators did not appropriately troubleshoot errors. Operators were reported to repetitively use a cobot while in an error state, potentially damaging the machine. This signals that there may need to be greater training to ensure operators can safely troubleshoot issues with cobots. Additionally, in work areas not designed to allow operators to visually monitor robots and check the status of the robot, operators may need to move the attention away from their tasks (Sauppé & Mutlu, 2015) and handling mishaps during (de)-commissioning may occur increasingly.

Clear interaction mechanisms ensure that humans can communicate with robots intuitively while understanding its intentions and movements. On the one hand, defining inputs or programming the robot should be intuitive and easy for workers. On the other hand, the information provided as feedback by the robot should be presented in an easily interpretable way to workers, so that they can have clear awareness of the system at any time (Villani et al., 2018). Sometimes the status of a robot is presented in a form or code that is not easy to interpret for workers that do not have a high level of expertise. The difficulty of learning how to use cobots can increase existing stresses for workers who are concerned that they may lose their jobs. Similarly, human actions often need to be communicated by pressing buttons, which are not always within close proximity (Michalos et al., 2014). Typically, humans would naturally communicate by using a combination of voice and gestures, and this allows them to convey information that can be either complementary or redundant. For example, an operator could say *"take this!"* while pointing at a specific object. The project "FourbyThree", developed by the European Union, proposes customisable solutions for human-robot collaboration and it is able to interpret information coming from multiple channels to understand voice and gesture interaction (Maurtua et al., 2017). While the FourbyThree project is promising for the future of cobots, research participants made it clear that it was much more difficult to quickly communicate and anticipate the actions of a cobot in the way that is a seamless interaction with human co-workers. While the interview study did not note any recommendations from end users for voice and gestures, they confirmed that hand-guided operation was much more intuitive and comfortable to use.

Users were often expected to conform to work in ways that were easier for cobots to understand. This imbalanced relationship can add additional strain to operators who may already feel as though they have limited agency when working with cobots.

Ethical risks and harm

Ethical risks involve a variety of aspects related to social factors. As defined by BS 8611 (British Standards Institution, 2016), ethical hazards are any "potential source of ethical harm", that is "anything likely to compromise psychological and/or societal and environmental wellbeing".

Social environment

Introducing cobots in the workplace also affects the social environment of a workplace. Some workers may fear that with the introduction of cobots into the workplace they might lose contact with their colleagues (Bröhl et al., 2016; Gervasi et al., 2020). Other research has demonstrated that as workers often engage in small talk with their colleagues while completing tasks, they sometimes wished cobots could do something similar. They agreed that the addition of speech and a screen as an information display would be beneficial (Sauppé & Mutlu, 2015). This desire to speak to a cobot or engage in small talk with co-workers was not flagged in our interviews with research participants.

Social impact

Introducing cobots into the workplace affects the social dynamics often leading to a change in the roles of some workers. While most interview participants appeared excited about the future of upskilling workers to operate cobots, there seemed little consideration to the loss of artisanal knowledge and skills that may occur. Cobots also have impact upon an operator's agency in feeling a sense of ownership and responsibility over their work. This may contribute to a devaluing of the knowledge and skills that they may possess. We identified two varied examples of this risk in medical and manufacturing settings. The agency of surgeon's knowledge and skills may be challenged by a cobot that is tasked with observing the surgery and preventing the surgeon from conducting incorrect actions. In interviews with a supplier, they highlighted that in manufacturing settings programming task applications for cobots was typically conducted by more senior personnel. Operators were reported to simply turn cobots on and off and the beginning and end of their shifts. It was reported in the interviews that operators enjoyed the ability to easily tailor cobot programming to mould to their working style and knowledge of specialist task applications. This indicates that a lack of operator engagement in programming cobots may contribute to a lack of worker agency and overall acceptance of cobots in the workplace.

In terms of social dynamics, as collaborative robots play a "co-worker" role, operators relate to them as social entities and their introduction into the workplace affects workers' perception. In the interview study, most participants responded that they perceived cobots more as a tool than a co-worker. Additional research on social implications of cobots in industrial settings has revealed a series of mechanisms that occur in this context. Operators perceive their relationship with cobots as human-like, and in some instances, they refer to the robot as *"work partner"* or *"friend"*. Cobots intrigue people to engage with them by appearing to have personalities show how they mimic human movement or tasks. Although in most cases workers describe their relationships as cordial, in a few instances they highlighted negative aspects, but still in familial or relational terms. Accordingly, operators attribute personality traits or intent to the robot (Sauppé & Mutlu, 2015). In terms of potential change in roles, the introduction of cobots often induces fear for job losses among workers (Maurtua et al., 2017; Sauppé & Mutlu, 2015). When cobots were introduced to a new site, several integrators and suppliers commented that most workers were cautious to engage.

Social acceptance

The likelihood of a community to accept the introduction of cobots is related to the predisposition to accept technology. In general, technology acceptance can vary within communities and it can be positively affected by the creation of workforce awareness (Gervasi et al., 2020). In an interview with an integrator, they claimed that brand new factories would be the only setting in which they wouldn't anticipate workers sabotaging cobots, as there was simply no workplace structural history for cobots to change in the first place. Distributors noted small to medium sized enterprises were more likely to be accepting of new changes such as cobots as management often includes and consults workers in the adoption of new technologies.

Data collection and privacy

Considering that cobots capture an array of data from their safety systems, there is a risk that operators and user data may be collected, used, and sold without user consent. In the interview study it became clear that many organisations in the industry were already interested in the potential value of this data in the development of future products and services.

Finding 2: Risk assessment tools and models for risk mitigation

Different metrics and models are available to assess physical risks, and in getting easier to quantify the risks. However, as recent research has also focused on psychological and ethical aspects, new models based on questionnaires have been developed around these risks.

<u>Risk assessment indices and approaches for physical risks</u>

Robla-Gomez et al. (2017) have reviewed the existing studies that quantify the potential consequences to the human body in case a collision occurs. Accordingly, different parameters allow to quantify injuries based on what part of the body has been involved in the collision, thus providing useful metrics to quantify physical hazards (see Table 10).

Table 9 - Injury indices to quantify physical risks in human-robot collisions (Robla-Gomez et al., 2017)

Body Area	Injury Index
Head	WSTC (Wayne State Tolerance Curve) HIC (Head Injury Criterion) 3ms-Criterion GSI (GADD's Severity Index) MPI (Maximum Power Index) MSC (Maximum Mean Strain Criterion)
Chest	VC (Viscous Criteria) Compression Criterion Force Based Criterion Acceleration Criterion TTI (Thoracic Trauma Index)
Neck	NIC (Neck Injury Criterion)

Although the standards specify what safety measures are required for the implementation of human-robot collaboration, a risk assessment needs to be performed in order to list all the possible risks involving physical hardware and to map them against the actions required to mitigate them. This also allows using the risk assessment map to specify the risks for each operative phase. For example, in the EU funded project ROBO-PARTNER, a specific scenario lists the operative phases and for each phase specifies the robot task, the operator task, the type of hazard and the safety method/s associated (from the four modes specified in the standards) (Michalos et al., 2018). Table 11 and Table 12 provide an example and illustrate of the risk assessment carried out for the project. The safety method in these tables refer to collaborative operative modes from Table 8.

Table 10 - Example of identified hazards through risk assessment (Michalos et al., 2018)

No	Hazard name	Safety method
1	Impact with robot arm during initiation	SSM
2	Impact with robot arm	SSM + HG
3	Impact with robot wrist	SSM
4	Impact with robot gripper	SSM
5	Impact with robot part	SSM
6	Crushing between gripper and fixture	SSM
7	Crushing between part and fixture	SSM
8	Crushing between arm and fixture	SMS + HG
9	Crushing between arm and non-supporting structure	SMS + HG
10	Trapping in arm linkage	SMS + HG
11	Trapping clothe/hair between axes	SSM
12	Trapping in wrist joint	SMS + HG
13	Trapping finger in gripper	SSM
14	Robot/Operator Cutting - With part: axle	SSM
15	Robot/Operator Puncture - With part: axle	SSM
16	Friction with part	SSM
17	Impact/Crushing/Puncture on the head/face with the robot	SSM
18	Operator startled by motion without fences	SSM
19	Intrusion of unauthorized persons in the HRI zone	SSM
20	Impact during transitions between non-collaborative and collaborative operation	SSM
21	Impact during transitions between collaborative and hand guiding operation	SSM

Table 11 - Example of a rear axle collaborative scenario (Michalos et al., 2018)

Phase	Name	Robot task	Operator task	Hazard number (Table 11)	Safety method
1	Load axle in the assembly table	Load axle in automatic mode	Free move out of the area	1-9, 14-19	SSM
2 (a)	Load right drum	Load drum in low speed close to the axle	Approach assembly table & insert cables	1-9, 14-21	SSM
2 (b)	Load left drum				
3 (a)	Guide robot to screwing position for right drum	Category 2 stop – wait to be guided	Guide the robot in the desired position	6-16	SMS+HG
3 (b)	Guide robot to screwing position for left drum				
4 (a)	Screw right drum	Hold the drum in the desired position	Screw the drum on the axle	6-16	SMS
4 (b)	Screw left drum				

Survey models for psychological risks

In order to measure human and cognitive factors, different parameters and models can be used. Some of the most popular parameters include mental workload, situation awareness, trust automation, and mental models (Vasconez et al., 2019). Charalambous et al., (2016) proposed a model to survey several psychological factors involved with the introduction of cobots into industrial workplaces. The psychometric scale developed by the authors is presented in Table 13. The model is based on an empirical study with small scale robots that pick up and hand pipes to the participants

Table 12 - Psychometric scale (5-point Likert) to survey human-robot collaboration (Charalambous et al., 2016)

Item	Description
1	The way the robot moved made me uncomfortable
2	The speed at which the gripper picked up and released the components made me uneasy
3	I trusted that the robot was safe to cooperate with
4	I was comfortable the robot would not hurt me
5	The size of the robot did not intimidate me
6	I felt safe interacting with the robot
7	I knew the gripper would not drop the components
8	The robot gripper did not look reliable
9	The gripper seemed like it could be trusted
10	I felt I could rely on the robot to do what it was supposed to do

Unclear interaction mechanisms can also pose a risk to the psychological wellbeing of workers. To this end, Gervasi et al. (2020) have summarised the information exchange dimension based on the work of previous authors (Goodrich & Schultz, 2007). These are presented in Table 14.

Table 13 - Summary of information exchange dimensions (Gervasi et al., 2020)

Level	Description of level for communication medium	Description of level for communication format
0	No senses are involved in the communication (i.e. communication with the robot is not possible)	No means of communication between humans and robot

1	At least a sense between sight, hearing and touch is involved in communication	Information is exchanged only through a control panel and/or display
2	At least two senses between sight, hearing and touch are involved in communication	At least a human-natural way of communication is employed (e.g. gestures, natural language) (control panels and displays may still be implemented)
3	Sight, hearing and touch are involved in communication	At least two human-natural ways of communication are implemented (control panels and displays may still be implemented)

Survey models for ethical risks

Bröhl et al. (2016) propose a model to survey social acceptance of robots in industrial settings. The survey takes into account multiple factors that range from context-specific items to aspects related to the interaction between humans and robots. Table 15 summarises the items (Bröhl et al., 2016; Gervasi et al., 2020), where it is important to note that although the model refers to social acceptance, many of the items include the psychological and social risks presented earlier.

Table 14 - Items and factors from Bröhl et al. (2016) social acceptance model

Factor	Description
Subjective norm	In general, the organization supports the use of the robot
Image	People in my organization who use the robot have more prestige than those who do not
Job relevance	The use of the robot is pertinent to my various job-related tasks
Output quality	The quality of the output I get from the robot is high
Result demonstrability	I have no difficulty telling others about the results of using the robot
Perceived enjoyment	I find using the robot to be enjoyable
Social implication	I fear that I lose the contact to my colleagues because of the robot
Legal implication (occupational safety)	I do not mind if the robot works with me at a shared workstation
Legal implication (data protection)	I do not mind, if the robot records personal information about me
Ethical implications	I fear that I will lose my job because of the robot
Perceived safety	I feel safe while using the robot
Self-efficacy	I can use the robot, if someone shows me how to do it first
Robot anxiety	Robots make me feel uncomfortable
Perceived usefulness	Using the robot improves my performance in my job
Perceived ease of use	My interaction with the robot is easy
Behavioural intention	If I could choose, whether the robot supports me at work, I would appreciate working with the robot
Use behaviour	I prefer the robot to other machines in the industrial environment

Finding 3: Holistic approaches to risks and harm and mitigation strategies - case studies

The raising of awareness of a wider range of risks and harm related to the adoption of human robot collaboration has been shown by recent industrial applications, which have used a holistic approach towards risk management. This section presents two case studies to demonstrate the holistic approach towards risks, and showcases mitigation strategies.

ROBO-PARTNER Project

The European Union funded ROBO-PARTNER, a project started in 2013 with the goal of demonstrating the feasibility of human robot collaboration assembly in the automotive industry. The project uses several safety practices and technologies that aim to reduce the physical and ergonomic impact, enable safe collaboration in which robots take the demanding tasks, increase the awareness of the robot operation status as well as a sense of comfort and acceptance, and support operators handling multi variant production. Physical risks are determined through a detailed risk assessment that maps all the operation phases against risks and required safety methods, as specified by the standards (see examples in Table 7 and Table 8). As a result, dynamic safety zones can be designed with the help of 3D simulation and then implemented in the assembly cells. In respect to psychological risks and in particular the need for clear interaction mechanisms, instead of using static features and hardware buttons, operators use an easy to use and intuitive system for continuous update of the execution status (see Figure 14 A). Thus, information exchange occurs through Augmented Reality (AR) and a smartwatch device (see Figure 14 B). Together, they allow multiple communication functions including:

- interfaces for AR applications such as display/hide, display/hide 3D parts models, display/hide robot working volumes, display/hide text instruction and display/hide production information,
- enable/disable manual guidance of the robot,
- stop/resume robot movement functionality,
- interfaces for requesting consumable parts,
- QR-code based pairing of the watch with the AR glasses,
- audio commands functionality to mode the robot.

Introducing intuitive and user friendly tools allows not only to have clear interaction mechanisms between cobots and humans, but also to increase a sense of comfort and acceptance within operators (Michalos et al., 2018).

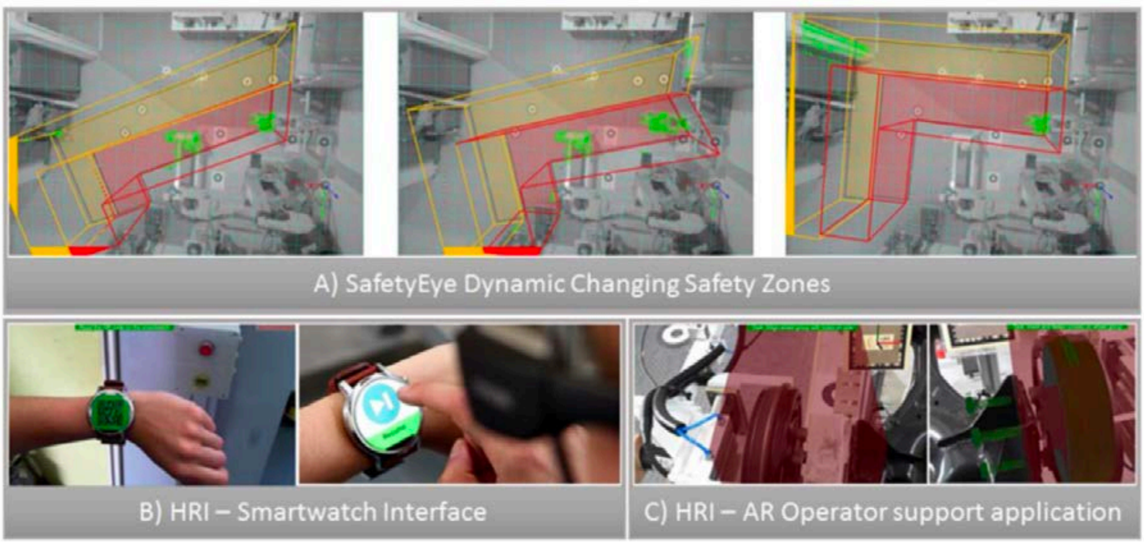

Figure 14 - Safety measures for human-robot collaboration assembly (Michalos et al., 2018)

FourByThree

FourByThree is an EU funded project that started in December 2014 to demonstrate the capabilities of human robot collaboration in manufacturing applications. Similarly, to ROBO-PARTNER, the project employs a variety of safety measures to reduce both physical and psychological risks. In regard to physical hazards, using actuators allows implementation of variable stiffness strategies as well as reactive behaviours in case of contact or collision with operators occurring. In addition, clear interaction mechanisms are at the core of the strategy to address psychological risks. Therefore, a semantic approach is adopted to enable information exchange through different channels in both a complementary and redundant way. This model is based on four main components: (1) a knowledge manager describing the environment and the feasible actions for the robot, (2) a voice interpreter, (3) a gesture interpretation module, and (4) a fusion engine that combines vocal and visual inputs to define commands for the robot. The approach allows operators to communicate with robots in an intuitive and natural manner. Based on experiments carried out within the project, workers' opinion was surveyed in order to investigate their perceptions in relation to the potential introduction of cobots into factories. In terms of key requirements for a successful implementation of human robot collaboration, safety has been considered the primary element (see Figure 15).

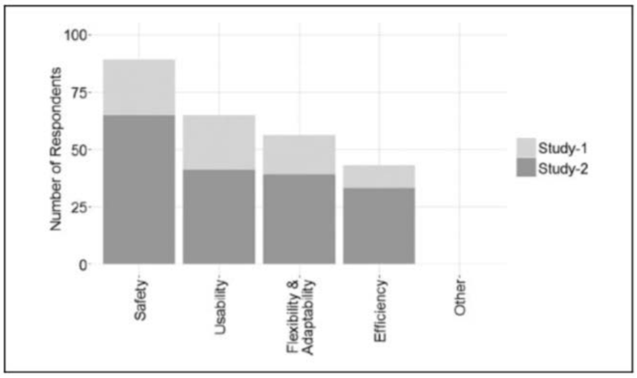

Figure 15 - Workers opinion survey A (Maurtua et al., 2017)

In terms of potential impacts, a series of positive effects was mentioned by participants, including improvements in productivity, quality of production, competitiveness and working conditions (see Figure 16). However, as mentioned within the ethical risks, the fear for job losses was also widespread (Maurtua et al., 2017).

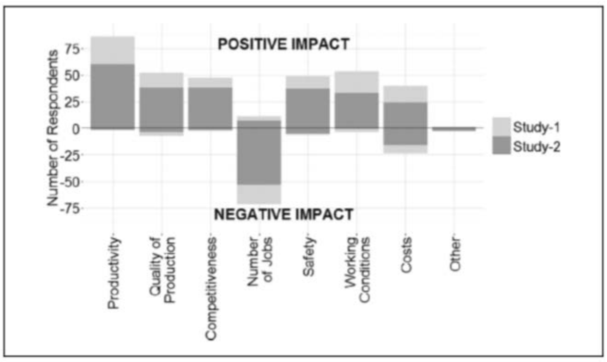

Figure 166 - Workers opinion survey B (Maurtua et al., 2017)

Discussion and implications

Cobot or robot – that is the question

A prominent issue identified in the interview study was that users implemented cobots for inappropriate applications. This issue was caused by unclear definitional boundaries and use-cases between cobots and industrial robots. Research participants often used the terms 'robot' and 'cobot' interchangeably to describe human-robot collaboration. If left unclear, end users may use their industrial robot for collaborative use or misuse cobots for non-collaborative applications. The following section will explore emerging patterns and implications upon cobot safety for use cases outside of the clear conceptualisation of a cobot, either using industrial robots for collaborative applications or using cobots for collaborative applications.

Industrial robots for collaborative applications

While the standards and the literature review clearly differentiate between industrial robots and cobots; the industry has progressively blurred this line by introducing products that convert existing industrial robots for collaborative use.

> *"I do know of some products that can be installed on industrial robots that make them behave like cobots. I think they're called Airskin I think something like that. Where if the capacitive pads make contact with the human, they basically stop instantly, it's almost like an e-stop" – Integrator*

Airskin is a modular, add-on safety peripheral that enables human robot collaboration for industrial robots (Wohlkinger & Baldiner, 2021). It is marketed to enable fenceless applications and faster collaborative movement than traditional cobots. It should be noted that distributors and integrators stressed the importance of slower speeds for collaborative robots as critical in minimising serious harm caused by collision. Furthermore, considering that Industrial Robots are not designed for collaborative use, it is also important to consider whether they have the computational power to adequately run safety detection programs in appropriate time to prevent hazardous collisions.

Although interview participants were aware of the potential of industrial robots for serious harm, they also acknowledged that there was a strong business case for converting industrial robots for human-robot collaboration. However, as industrial robots operate at much faster speeds and higher payloads, collaborative applications can significantly increase the potential for serious physical and psychological harm.

> *"...It [industrial robot] doesn't stop in a safe manner. I've seen robots collide with conveyors and basically bend them. And then it will stop." - Integrator*

As the business case for human-robot collaboration continues to grow - especially for small to medium sized enterprises - in Australia, there will be greater interest in innovating existing industrial robots to operate more collaboratively. This was reflected in the interviews when a researcher shared that they were actively working on converting an industrial robot for collaborative use.

> *"We're trying to think of cobots as robots that can work closely with people and in fact they don't need to be this so called cobots that people are selling as cobots. We think some cobots may be much bigger robots, we've got a 200 kg payload robot here that we want it to be a cobots in some situations. Because it's about how it performs, not about some arbitrary label that says 'it can do this' because if it's set up correctly and we can verify it set up in the right way…Then there's no reason why it also can't be a Cobot." – Interviewed researcher*

Cobots for non-collaborative applications

> *"A safety system is safe unless an operator needs an extra tool to sort of defeat it." - Supplier*

It became clear in the interview study that users assumed that cobots were inherently safe, meaning that they did not prioritise human safety as their main consideration for using cobots. While cobots have safety features that help minimise harm and comply to standards that make them safer for collaborative use compared to industrial robots; the danger of marketing them as 'safe alternatives' can lead users to assume that cobots are safe and appropriate for any application that requires collaboration. This expectation was exemplified when speaking to a potential purchaser of cobots, who explained *"you don't have to worry about the risks with cobots"*. As this interview participant was an executive driving the future of a major manufacturing industry in Australia, there are large-scale ramifications for this type of assumption. This was a consistent response when users were asked about specific risks and harms associated with cobots.

> *"I can go and sell a collaborative robot but it doesn't mean that the application is collaborative". – Supplier*

The main contributor to non-collaborative applications was not the cobot itself but the task assigned to a cobot and the end effector. The most common example of how cobots could be used for non-collaborative applications related to the installation of a sharp end-effector to a cobot arm. In this example, a freely moving sharp object could never be safe for collaborative use with humans. Furthermore, an open blade in any workplace remains dangerous even if a cobot is turned off. This reveals an emerging misunderstanding in what exactly is 'safe' about cobots between cobot users, integrators, and manufacturers.

This misunderstanding of safety stems from misaligned expectations and definitions of what components are considered safe. Suppliers and manufacturers sell cobots as part machines. A part machine cobot comprises of four components; the manipulator (arm), controller/ cabinet (computer & drivers), connecting cable between manipulator and cabinet, and the teach pendant (human interface). As a part machine, suppliers and manufacturers can assure that these components are safe. The installation of an end effector was the only requirement to consider a cobot a complete machine. It appeared to be well understood that role of the integrator was to ‘complete’ the machine to the local standards, including installing end effectors and assessing the task application.

Users are not required to consult with integrators in order to purchase a cobot or to change the task/setting/tools that a cobot uses. ‘Plug-and-play’ cobots make it easier for end users to change the task application post implementation. In the case of integrated and/or ‘plug-and-play’ cobots, end users’ assume that it is safe for all applications. Users did not have a clear understanding of the difference between a part and complete machine and how that impacted upon safety. Suppliers noted that they were aware of this misunderstanding and suggested that there needed to be greater awareness surrounding what components they consider safe and where the responsibility of different aspects of cobot safety lay.

Limited consideration for psychological risks and harm

There appeared to be little consideration for the psychological harm that could occur when working with cobots. Research participants were asked questions regarding various psychological risks that could occur that were reported in the literature. However, despite multiple attempts, participants rarely shared insight into this area. The most prominent cause of distress raised by research participants was anxiety and stress caused by job precarity.

A cobot user responsible for managing operators offered their insight into this apparent gap in prioritising psychological risks. They suggested that the traditional cultural context of manufacturing and industrial workshops could make it difficult for operators to feel comfortable in openly and candidly discussing the psychological effects of working with cobots. The fear of being perceived as weak and valueless was touted as another factor that limited participant disclosure of psychological harms. As male-dominated industries, this culture has historically resulted in an under reporting of psychological impact of work upon workers. While outside the scope of this research, investigating the influence of gender upon the reporting of psychological risks would benefit from further research.

Industry-wide inconsistencies in ensuring cobot safety

The continued exponential growth of cobot usage has led best practices to lag behind innovative practices, which has resulted in cobot users developing ad-hoc approaches to safety. These ad-hoc solutions have left the industry with inconsistent risk mitigation and minimisation strategies.

Lack of appropriate testing of task application

Across the cobot industry there is an inconsistent approach to risk assessments and testing new task applications, work settings, or end effectors. A key insight was that only conducting simulations was an inadequate approach to assessing the safety of a task. Interview participants reported that end effectors were static objects in simulation and did not simulate debris -an essential consideration to ensure the correct set up of the workspace. Physical testing was inconsistently applied by end users. One interviewee shared a comprehensive tiered testing protocol that separated testing into different stages; simulate, test task with cobot arm only, test with end effector turned off, test with end effector on, test with material, and then finally test collaborative operation. In order to continue encouraging innovative uses of cobots whilst also ensuring safety, there needs to be greater consideration of the design of testing processes that ensure that all facets of the interaction are safe.

Varied minimum training requirements

The interview study identified a discrepancy in what different players in the cobot industry understood as essential competencies, skills, and training that are required to safely use cobots. It was highlighted that there is an inconsistent approach to training across the cobot industry. Research participants' responses indicated varying expectations regarding minimum competencies, skills, and training required to safely use cobots. For some, the entry to engage with cobots was a simple induction program, with these inductions themselves varying in duration from a few hours to a few days. While some research participants confirmed that they had engaged in some form of formal training, this was not consistent across all interviews. Research participants reported that many staff learn by demonstration, on-the-job training, or through experimentation and use. Operators reported that experimenting and testing functions on cobots helped them understand how to use them for specific tasks. However, only one interview participant indicated that they tested programs and function prior to collaborative use. Similarly, cobot users and integrators interviewed reported that operators were often not taught how to safely troubleshoot issues with cobots. It is critical that this knowledge gap and dimension is addressed as errors and issues with cobots can increase the risk of physical harm, damage to cobots and other equipment, and psychological strain for operators.

Research participants had not considered how to ensure compliance with training when faced with a revolving door of new workers interacting with cobots or for staff who are not directly working with cobots. This was a considerable concern for industries with low staff retention rates where training new staff to work with cobots may be time-consuming and expensive. One way that this could be addressed is by integrating cobot training into vocational and trade schools. In interviews with cobot researchers and manufacturers, participants indicated that vocational schools had already begun to incorporate modules to educate students on how to work collaboratively with robots. This sentiment was also echoed by the CEO of a peak body for a manufacturing trade. While this is a promising step forward for the industry, it neglects to acknowledge the tradespeople who already have extensive experience but minimal training in working with cobots and computer interfaces.

Multi-dimensional approach to cobot safety

In the interview study it became apparent that additional dimensions are needed to comprehensively address all factors that may contribute to risks and harms. End effector and task assignment emerged as potential additional dimensions. To address the risks in the larger cobot system, enterprise and contextual factors must also be considered in the development of safety standards and guidelines. In the interview study it became clear that what drew many users to cobots was their diverse usage and ability to enhance outputs. However, the risk in prescribing standards by industry or use-case is that they may discourage users from utilising cobots to develop new solutions and products. It was evident that users have an unclear understanding of the risks and harms that can emerge with human-robot collaboration. To continue encouraging innovation in cobots and among industry and mitigate risks and harms, it is important that standards support safe innovative practices and address common misunderstandings that users have relating to cobot risks and harms.

To comprehensively encourage safe and innovative practices for human-robot collaboration, these key considerations are recommended in the development of safety guidelines:

I. What is a collaborative application for this machine?
II. What aspects of cobots/robots are guaranteed as safe and by which stakeholders?
III. When considering this machine as co-worker; explore the potential risks and harms that a human could experience in this application.
IV. When considering this machine as a tool: explore the potential risks and harms that could occur if this was another tool (e.g. interaction mechanisms, maintenance, and secured end effectors).
V. When and how should applications be tested and risk assessments be conducted?

These principles have been developed by understanding the contextual and human factors that may increase or contribute to risks and harms associated with human-robot collaborative tasks. The principles purposefully include industrial robots when considering safe and innovative human-robot collaboration. In doing this, the future development of guidelines can capture a wider array of users who might be unaware of the term cobot, misunderstand collaborative applications, and/or are considering human-robot collaborative work practices in the future. Misunderstanding these principles can result in inappropriate task applications, dangerous use of end effectors, and hazardous work settings.

Conclusion

Three main categories have been defined based on the type of harm that the risks can have on workers: physical, psychological and ethical.

Physical risks and harm

The most common physical risk theme within the literature refers to potential collisions with robots while sharing the same space in order to collaborate. Conversationally, the ability to identify these possible malfunctions - or the likelihood to malfunction - was not seen, by operators, as easy to pre-empt or manually check within existing cobot design and sensor placement. Uncontrolled movement and loss of movement can also place the human user at risk of possible collisions, due to inconsistent and unreliable movements. It is not only the machine itself colliding with the user; debris, a by-product of tasks, are hazards that need to be considered. In addition to collisions, the most common injury to the user was described as pinch points, where the users can be pinched by the cobot mechanics.

Cobots are more portable than typical industrial robots, often with dynamic work cells. This alone affects the workplace and safety profile. Any guidelines will need to include the workplace or cobot work cell; the whole cobot ecosystem including the user. Portability, while bringing increased and more sophisticated functionality, can affect the surrounding safety and risk.

Cobots are likely to be used by more than one user and bring risks concerning human ergonomics. Collaborative robots can potentially improve working conditions for operators by providing benefits including the reduction of physical and mental loading. However, calibration for different users was highlighted in the research and includes positioning to support human user ergonomics. Regardless of the type of robot, factors such as the dimension of the workplace, and the setup of appliances, boxes and tools should meet ergonomic requirements and be considered in the risk profile.

The personalisation of the cobot to the task at hand not only included portability, but also the use of different end-effector attachments. The end-effectors may be included by the manufacturer or made internally based on the operator's understanding and expertise relating to the job to be done. In these cases, guidelines will need to balance risk with increased functionality.

The connectedness of cobots within the workplace can lead to cybersecurity risks. Inadequate safety validations or considerations allowing unauthorised access and sabotage; technological causes such as manipulated control components; malware infiltrated through hardware, inter- or intranet; or even limited accessibility for an intended use can result in physical harm for operators, e.g. due to unexpected movements.

Psychological risks and harm

Psychological risks due to operator behaviours include many areas that influence how the human operator interacts safely or otherwise with cobots. The identified areas of psychological risk include stress, mental strain, and complicated interaction mechanisms.

The primary contributor for stress was the perceived risk of job loss for workers and specialist tradespeople. This was typically underplayed by suppliers and distributors who explained that cobots would only replace conventionally undesired work that was dirty, dangerous, or repetitive. It remains unclear whether this claim is supported by others in the industry. The risk to the agency of the worker is also an important to consider. When operators are expected to conform to working in ways that are easier for machines to understand, it can add additional strain to operators who may already feel limited agency in completing a work task.

Unpredictable movements and collision can make users feel nervous. Consistent mental discomfort leaves operators mentally strained and unfocused on operation and increases their risk of accidents. Further contributing to a lack of focus is the repetitive and tedious actions of some human-robot interactions which made operators feel fatigued, tired, or bored. Across the industry there are unclear standards of maximum allocated operation time which may result in greater further strain.

Complicated interaction mechanisms can also impact upon concentration and situational awareness. The difficulty of learning how to use cobots can increase existing stresses for workers who may be already concerned with their potential job displacement. It's also important to consider the strain caused by lack of intuitive communication between human and cobots which make tasks more tedious for operators.

Ethical risks and harm

Ethical risks primarily relate to the social aspect of cobot use. The research highlights the importance of the social environment needs of the user, social impact and co-worker status as well as social acceptance. All being key driving forces of acceptability and safe use. The literature reviews and interview study at this time has effectively identified key risks and possible harms that build the basis for safety guidelines. The interview study highlighted that risk assessments and testing for all risk factors were inconsistently applied across the industry. Physical and more technical risks are easier to quantify. Injury indices are available to quantify physical risks. Survey models exist to quantify psychological risks as well as information exchange dimensions. The team have also uncovered a model by Bröhl et al. (2016) that includes positive and negative social acceptance and ethical risk identification. These methods of quantification will be considered as the project advances to guideline co-design. In this report we refer to two case studies that have included a holistic approach to risk management quantification in industrial settings.

Additional insights

The findings revealed gaps that must be considered in order to improve the safe implementation and use of cobots.

1. Cobot users lack a strong understanding of the differences between collaborative and non-collaborative robotic interactions. Furthermore, there is a need for clearer distinctions of collaborative, cooperative, and coexistive interactions cobots can have with humans.
2. In the post-implementation stage, there is a large inconsistency across cobot users in how they conduct risk assessments and testing procedures for new task applications, work settings, and/or tooling such as end effectors. Furthermore, there is an inconsistent approach to training across the cobot industry which makes it difficult to establish baseline competencies, skills, and knowledge that cobot users need in order to safely work with cobots.
3. There is a lack of holistic understanding of cobot safety across all stakeholders, with greater emphasis on the physical design of the cobots. This neglects to consider other socio-technical dimensions including the design of work cells and workplaces, training, organisation, and processes.

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Appendices

APPENDIX A: Work Package 2 – Participation Letter

Dear [NAME]

University of Technology Sydney & Centre for Inclusive Design are excited to collaborate on a research project for the Centre for Work Health and Safety.

The project aims to understand how organisations can safely introduce and work with autonomous, collaborative robots (Cobots). Further information and confirmation of the collaboration can be found here

We are looking for participants in the form of manufacturers, suppliers, integrators, cobot user companies, potential cobots user companies and industry partners to participate in the project.

Participation will be in the form of interviews, focus groups and design-led workshops. While there are several aims of the project, the final output will be safety frameworks and guidelines. Participants may have the opportunity to c o-design and then evaluate these artefacts in real-world settings.

We have identified your organisation as fitting our participant profile and hope you would consider contributing. This project represents an opportunity to contribute to policy as well as connect with those in the industry.

Participants will be asked to spend 1 to 2 hours with us at a time that suits them. We will be asking for their feedback on the work health and safety aspects of Cobots. In addition, your organisation may be asked to be part of a codesign session later next year.

Initial interviews and focus groups will be held in September.

If you are interested, please reply all and the Centre for Inclusive Design will be in touch.

APPENDIX B: Work Package 2 – Sample Interview Question Guide

University of Technology Sydney & Centre for Inclusive Design are excited to collaborate on a research project for the Centre for Work Health and Safety.

Introduction – 5min

Thank you [name] for making time to speak with us. Before we start, I just want to let you know that if you would like to stop the session, please let me know at any time.

I'll start by acknowledging the traditional owners of the lands where we meet today. Paying my respects to the Elders past, present and emerging. (I extend that respect to you here today).

These interviews sit in our discovery phase, and the purpose of today is to identify risks and harms you think can occur when we work with Cobots. Loosely sitting in three groups.

1) *Physical harms and risks*
2) *Psychosocial and ergonomic; and*
3) *Ethical*

These interviews are a part of a larger project working with UTS and on behalf of the Centre for Work Health and Safety. At the end of this project, we are looking to develop guidelines and strategies with the industry for safe human/cobot interactions.

Obviously, there are no right or wrong answers – really this is more of a scoping exercise to see where the industry is right now. I might ask questions where the answer seems obvious, this is just so I am not assuming anything and fully understanding your perspective.

Everything shared today of course will be confidential and anonymised if it needs to be 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.

This helps me from missing out on anything important. It won't not be shared anywhere and will be safely stored and deleted once our report is complete.

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

Warm up – 10min

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

- What sort of work do you do? What does your day to day look like?
- What other hats do you wear in your life? E.g. parent, carer, volunteer, etc

Cobot Users and Purchasers

Introductory Questions:

- Why did you decide to get into this business?
- Where do you sit in the market?
- What are your key productions?
- Who are your key customers?
- Can you think of a time where you introduced something novel and/or risky into the workplace? What was that experience like?
    - What did you learn from that experience?
- What does safety mean to you?
- What drew you to Cobots?

Focused Questions:

- Cobot Design:
    - What were the key features that influenced your purchasing decision?
        - How did you know cobot was safe?
    - What was the purchasing experience like?
        - Were you provided with any information and support? *Who supplied this? Were they helpful? What would you have added to this?*
    - Did you make any additional purchases for cobots tasks?
    - What features would you like to see in newer models?
- Organisation Design:
    - What are some of the typical tasks that are assigned to Cobots in your organisation?
        - *Is it configured differently for different tasks/objects?*
    - How many people interact with cobot? *What capacity do they engage in it?*
    - Would you consider the cobot a tool or a co-worker or something else?
    - What is your role and responsibility in the cobot ecosystem?
    - What expectations do you have of the cobot in mitigating risks and harms?
- Training Design:
    - How did your staff learn to work with cobots?
    - What skills and competencies are important when working with cobots?
    - What do people tend to forget when using the cobot?
    - What was the steepest learning curve in implementing and using cobots?
- Process Design:
    - Do you have any systems and processes that cover Cobot interactions?
    - Did you need to change any processes when Cobots were introduced? How?
- Workspace / 'Cell' Design:
    - What environments do you think work best for cobots?
    - Where do cobots fit into your organisations workflow and workspace?
    - How is your workspace set up?
        - Did introducing Cobots change how the workspace was set up?
            - What immediately surrounds the cobots?
    - What situations are not ideal for cobots – why, why not?

Suggestive questions:

- What would you recommend to other organisations that are interested in purchasing Cobots?
- What are good resources for establishing safe human cobot interactions?
- Where do you think the industry is heading?
  - Where is the future of Cobot safety heading?
- What do you think needs more consideration when it comes to safe human cobot interactions?

Suppliers, Distributors, & Integrators

- General Questions:
  - Why did you decide to get into this business?
    - Where does your business sit in the market?
    - What are your key products?
    - Who are your key customers?
  - How did you enter the cobots industry?
    - *Was there a gap in the industry? Growing call from businesses for cobots?*
  - What would you define as a cobot?
    - What makes cobots different from robots?
  - What does safety mean to you?
- Process Design
  - Could you talk me through the general process of integrating cobots into a new business?
    - Can you share a challenging experience in integrating cobot's into an organisation?
  - Do you have a system or process that you follow when integrating/supplying cobots?
  - What services do you provide customers?
    - What are some of your recommendations to organisations and businesses that are interested in working with Cobots?
- Cobot Design:
  - What key features do you think influence customer purchasing decisions?
  - What tasks are typically assigned to Cobots
    - *Is it configured differently for different tasks/objects?*
    - *Have you ever had to create a custom solution for a customer?*
  - As cobots grow in popularity, what do you think needs greater consideration?
- Organisation Design:
  - Would you consider the Cobot a tool or a co-worker or something else?
  - What do you think businesses responsibility is in ensuring cobot safety?
  - What do you think manufacturers responsibility is in ensuring cobot safety?
  - What is your role and responsibility in the cobot ecosystem?
- Work 'Cell Design
  - What environments do you think work best for cobots?
  - What situations are not ideal for cobots – *why, why not?*
    - *Could this change?*
- Training Design:
  - Where is the steepest learning curve in integrating cobots for customers?

- What skills and competencies are important when working with cobots?
    - What risks can be addressed with appropriate training? *What can't and how do you think we need to address this?*

Suggestive questions:

- Where do you think the industry is heading?
    - Where is the future of Cobot safety heading?
- What are good resources that would recommend to those interested in establishing safe human cobot interactions?
- What do you think needs more consideration when it comes to the risks and harms associated with human cobot interactions?
- As we said at the beginning, in the later stages of the research we are working to co-create guidelines for safe human cobot interactions;
    - What do you think would be important to include?
    - Who do you think we should address?

University (developing the cobots of the future)

- What are your research interests?
- What drew you to cobots and this industry in general?
- Where do you think the industry is heading?
    - Where is the future of Cobot safety heading?
- How would you broadly define what a cobot is?
    - What is it's role in the workplace?
- Where do you see the gaps in integrating cobots into workplaces?
- What do you think needs more consideration when it comes to the risks and harms associated with human cobot interactions?
- What systems and processes need to be developed to support this industries growth?
- What environments do you think work best for cobots?
- What situations are not ideal for cobots – why, why not? *Could this change?*
- What are some of your key recommendations to organisations and businesses that are interested in working with cobots?
- Where is the steepest learning curve in implementing and working with cobots?
- What skills and competencies are important when working with cobots?
    - What risks can be addressed with appropriate training? *What can't and how do you think we need to address this?*
- What risks and harms are present across different organisational settings?
- What are some of the concerns in large-scale adoption of cobots?
- What are some of the blindspots in the industry?
- What are good resources that would recommend to those interested in establishing safe human cobot interactions?
    - As we said at the beginning, in the later stages of the research we are working to co-create guidelines for safe human cobot interactions;
    - What do you think would be important to include?
    - Who do you think we should address?

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, they were incredibly useful in gaining insight into the associated risks and harms in human cobot interactions.

Now as I said at the beginning, this is really our discovery stage, 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?

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]