Received: 22 May 2023 | Revised: 14 September 2023 | Accepted: 18 September 2023

DOI: 10.1002/hfm.21014

RESEARCH ARTICLE

WILEY

Analysis of quality standards for industrial collaborative robots based on user-centered design framework

In Seok Heo | Alivia K. H. Putri | Beom Su Kim | Min Seong Kwon | Sang Ho Kim

Department of Industrial Engineering, Kumoh National Institute of Technology, Gumi, Korea

Correspondence
Sang Ho Kim, Kumoh National Institute of Technology, Department of Industrial Engineering, Gumi 39177, Korea.
Email: kimsh@kumoh.ac.kr

Funding information
National Research Foundation of Korea, Grant/Award Number: 2021R1A2C2095410

Abstract

Industrial collaborative robots have become increasingly important in recent years due to their ability to work safely and efficiently alongside humans. As a result, there is a growing need for evaluation standards to ensure the quality of collaborative robots. However, existing studies only consider system-centered and technical aspects of collaborative robots, and there is a lack of research on user-centered quality evaluation. In this study, we identified 21 user requirements based on a user-centered design framework and confirmed the limitations of existing quality standards by reviewing the standard clauses for collaborative robots. It was found that user needs to be related to performance, safety, and even usability and enjoyment are already being expressed according to the user-centered design framework, but the quality standards for these needs only present design principles or do not consider them at all. This study provides information on the quality attributes that need to be fulfilled to satisfy user requirements and suggests the need and direction for further research on the user-centered evaluation of collaborative robots. Accordingly, the user's perception and experience of collaborative robots are expected to improve.

KEYWORDS

hierarchy of human needs, industrial collaborative robot, quality standards, user-centered design, user requirements

1 | INTRODUCTION

Over the past three decades, industrial robots have been developed to replace humans in performing repetitive, dangerous, and tedious tasks (Gasparetto & Scalera, 2019; Hvilshøj et al., 2012). Traditional industrial robots have been deployed to perform tasks in workspaces separated from human operators by fences to increase productivity and reduce costs through automation (Hägele et al., 2016; Papavasileiou et al., 2022; Sandini et al., 2018). However, industrial robots cannot adapt efficiently to dynamic changes in manufacturing processes caused by manufacturing paradigm shifts, such as the production of customized products (Arents & Greitans, 2022). Collaborative robots, which can combine the advantages of robotic automation with the flexible thinking capabilities of human workers, are emerging as a solution to these problems (Faccio et al., 2020; Kadir et al., 2018; Perez-Ubeda et al., 2019).

Due to the growing importance of collaborative robots, the International Organization for Standardization (ISO) has published standards for industrial collaborative robots, such as ISO 10218 and ISO/TS 15066. Most of the proposed standard clauses present technical requirements in terms of system performance for operating a robot in a collaborative environment between a collaborative robot and a human operator (Francesco & Paolo, 2017). However, even if the specifications of collaborative robots satisfy a high level of performance, these system-centered standard clauses may cause problems with user trust and acceptance of new technologies in the actual commercialization stage of collaborative robots. In particular, collaborative robots equipped with artificial intelligence technology capable of knowledge-based behavior will enable more complex and diverse interactions (Borboni et al., 2023). A gap between the intentions of technology developers and the needs of users can lead to improper interactions that not only reduce user satisfaction but also lead to safety issues. To elicit intention to use and increase satisfaction, it is necessary to reflect on user needs when evaluating the quality of collaborative robots. However, existing standards only measure technical performance levels as an indicator of quality without considering user needs. To address these issues, it is necessary to shift toward a user-centered design approach, surpassing system-centric quality standards (Kaiser et al., 2018; Wang et al., 2019). User-centered design is based on ergonomic principles that consider the physical, cognitive, and psychological characteristics of humans when developing a product or system (Zöller, 2019). It focuses on the needs of users to improve the safety, efficiency, and satisfaction of the product (Lanter & Essinger, 2017; Still & Crane, 2017). In this respect, existing system-centered quality standards have limited the ability to incorporate ergonomic evaluation methodologies into the design approach. To apply ergonomic evaluation methodology to the technology development stage, there is a need to expand the concept of quality standards and redefine them according to the user-centered design framework.

The development of collaborative robotics has evolved from its early stages, when robots were perceived as a threat to human safety, to a point where robots and humans have collaborated to achieve common goals (Vicentini, 2021). Human–robot collaboration (HRC) is generally categorized into four levels: no coexistence, coexistence, cooperation, and collaboration (Aaltonen et al., 2018). With the advent of the Third Industrial Revolution, rapid industrialization, and automation, the concept of robots first appeared, and robots that perform tasks autonomously or semiautonomously through programming were introduced. In the early days of robotics, robots in the "no coexistence" level were designed to work in physically separated workspaces through fences, away from human operators, without collaboration (Oberer-Treitz et al., 2013). These robots were programmed to perform specific repetitive tasks and could not adapt to changing environments or collaborate with humans (Malik et al., 2020). The main focus at this level was to improve the functions of robots such that they could perform tasks more accurately and efficiently (Singh et al., 2013). As the 21st century progressed, robots became more capable owing to advances in sensing technology and information and communication technology (ICT), and collaborative robots at the coexistence level began to be deployed in collaborative spaces alongside human workers (Weiss et al., 2021). However, robots are designed to work separately from humans, and safety protocols must be developed to separate workers and robots to prevent accidents (Arents et al., 2021; Medina et al., 2019; Pedrocchi et al., 2009). The main focus of this level was to ensure the safety of the human operator from possible hazards around the robot, and it is currently the most widely applied HRC level in the industry (Murashov et al., 2016). Starting at the cooperation level, collaborative robots are designed to work alongside human operators, share tasks, and collaborate to achieve their respective goals (Hietanen et al., 2020). At this level, collaborative robots focus on improving Human–robot interaction (HRI) and should be designed to be more flexible and adaptable to work in dynamic environments where tasks and goals can change quickly (Dmytriyev et al., 2021). Although several researchers are working on efficient HRI (Kokotinis et al., 2023; Tzavara et al., 2021), numerous obstacles remain to be solved before collaborative robots can be commercialized (Borboni et al., 2023). At the collaboration level, robots and humans work together equally to share knowledge and technology, and accomplish a common goal (Chowdhury et al., 2020). At this level, the collaborative robot should learn from the human operator and adapt to its work style. This level should emphasize making the robot more intuitive and user-friendly to enable the human operator to interact with the robot more naturally (Chowdhury et al., 2020).

In this context, a user-centered design framework for ensuring the quality of collaborative robots should reflect the coevolving nature of technological advances and user needs, as shown in Figure 1. In general, user needs are not fixed but rather change in response to technological developments, social trends, and economic factors (Wang & Yu, 2016). With the increasing use of collaborative robots in various fields, it is essential to verify whether these robots

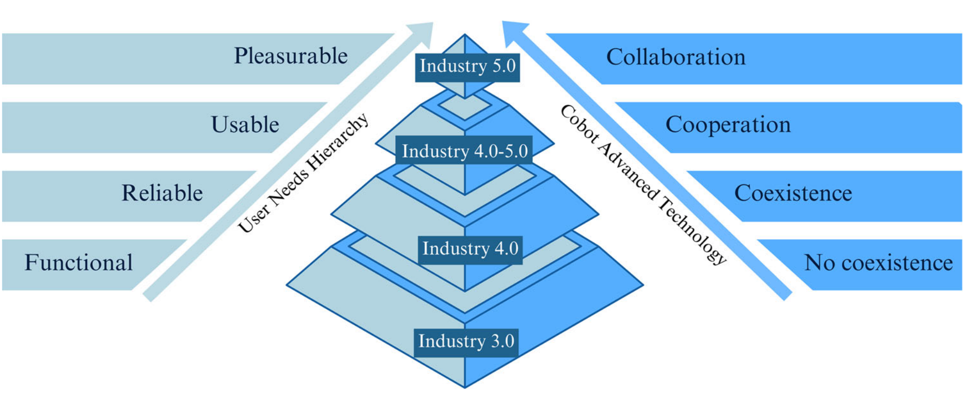

FIGURE 1 Technology–user needs coevolution.

satisfy the required quality standards (Box, 1983). The dynamic characteristics of user requirements that determine the quality of collaborative robots need to be identified and structured, and reflected in evaluation metrics (Franklin et al., 2020; Khamaisi et al., 2021; Prati, Peruzzini, et al., 2021). User-centered quality standards can help companies' developers, researchers, and decision makers to identify the individual fulfillment of user needs, which can be used to formulate technology management strategies during the technology development process. The design of user-centered ergonomic standards for collaborative robots to secure the technology acceptance and trust of human workers can be revived according to the needs of workers to prepare actively and efficiently for changes in the international business environment (Gualtieri et al., 2020; Pizzagalli et al., 2021; Prati, Villani, et al., 2021).

To identify the main challenges in setting up an industrial environment for HRCs, Kumar et al. (2020) proposed a conceptual taxonomy diagram for HRCs and identified quantitative metrics to evaluate the safety, performance, and productivity of HRCs. The study by Valori et al. (2021) outlines emerging needs and trends in safety test procedures based on an overview of safety-related collaborative robot standards, and proposes a new cross-domain approach based on safety technologies and test protocols. Segura et al. (2022) mention the insufficiency of safety standards related to collaborative robots and extend the safety standards baseline by analyzing how safety and related standards and technologies are integrated to transform collaborative robots into full teams with human workers. Despite this effort, no study has analyzed the clauses of the standards based on the requirements of the workers that may appear in HRC environments to consider their needs from an ergonomics perspective.

Therefore, by classifying the standard clauses applicable to collaborative robots according to user requirements, this study identifies the limitations of the existing quality standards and proposes design directions for user-centered collaborative robot quality standards that can facilitate the development of safe and effective collaborative robots for various industrial applications. The analysis of standard clauses according to the user-centered design framework is based on the analysis of various characteristics of user requirements and a thorough review of existing quality standards applicable to collaborative robots. Using a correlation matrix, this study identified the gap between user requirements and standards, and proposed solutions to resolve this challenge. These solutions enable manufacturers and regulatory agencies to assess the quality of collaborative robots by focusing on user-centered design.

2 | METHOD

This study aimed to determine whether existing quality standards fulfill user requirements for various attributes. Therefore, the steps for comparing the correlation between user requirements and existing quality standards are described. This study consists of three main steps: (1) identifying user requirements for collaborative robots through prior research and categorizing them according to the level of user needs, (2) comprehensively reviewing the existing standard clauses related to collaborative robots and the process of establishment and revision over time, and (3) mapping and analyzing the correlation between the standard clauses and user requirements to propose a design direction for user-centered quality assessment standards for collaborative robots.

First, previous studies in the field of collaborative robots were thoroughly reviewed to identify user requirements. Various user requirements in the HRC context were identified by reviewing previous studies, including academic literature and industry reports, that analyzed the factors influencing user perceptions and expectations of collaborative robots. The identified user requirements were categorized according to four levels of user needs, including functionality and usability. This categorization can help ensure that standard clauses are satisfied according to the changes and characteristics of user requirements as the technology of collaborative robots evolves. A comprehensive review of existing collaborative robot quality standard clauses was conducted as the second step in this study. In addition to reviewing ISO/TS 15066 and ISO 9283, which are standards related to the operation of collaborative robots and describe a method for evaluating the performance of manipulating robots, various standards, such as criteria for collaborative robots as control systems, machinery, and interactive systems, were comprehensively reviewed. A list of quality items was established based on a review of existing standards related to collaborative robots. Finally, the identified list was mapped to the user requirements for collaborative robots, categorized by the collaboration level. Thus, a matrix was created to map the user requirements to the quality clauses. This matrix was used to analyze the gaps between user requirements and existing quality standards. Several clauses in standards merely offer design principles or guidelines rather than technical specification requirements that can be quantitatively measured. The matrix provides information on the description level provided by the clauses to evaluate the extent to which existing standards reflect user requirements. The description was divided into the following three levels:

Principle: A principle is a fundamental concept that serves as the basis for assessment. Principles are general and abstract, and provide a framework for decision-making.

Guideline: A guideline refers to a set of recommendations that provide directions or suggestions for a specific activity. Guidelines are more specific than principles and provide practical advice on following a particular assessment process.

Standard: A standard is a specification used for quality assessment. Standards are quantitative and specific, and provide consistency in the assessment process.

The comprehensive research process is illustrated in Figure 2. The matrix demonstrates the gaps between user requirements and standard clauses, and establishes a direction for designing quality standards to address this challenge.

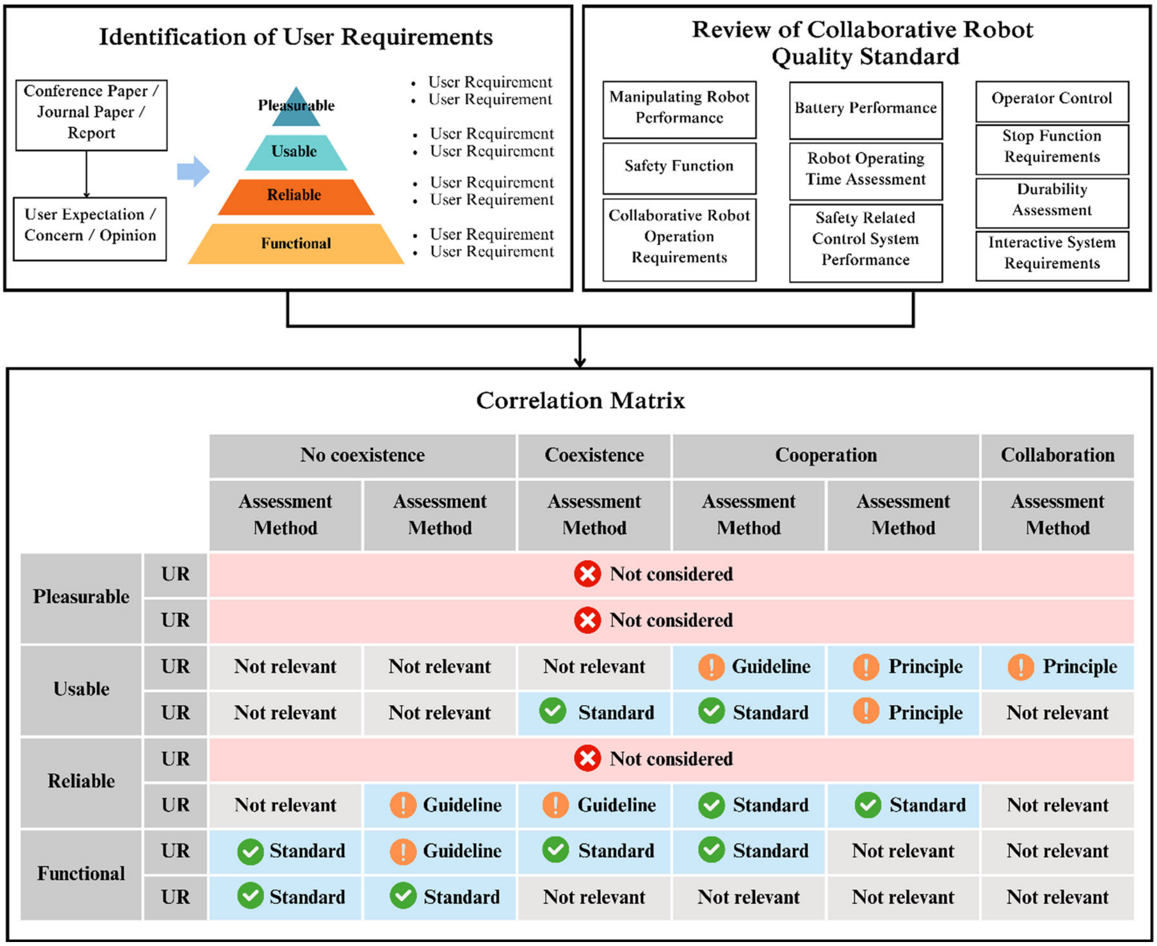

FIGURE 2 Research process.

3 | RESULTS

3.1 | Definition of user requirements

In previous studies, user requirements identified through factors influencing the user perceptions of collaborative robots, such as safety, usability, and reliability, were classified and redefined according to the level of collaboration (Table 1).

The CoLLaboratE Project (2020) identified user requirements by industry domain through an online questionnaire to utilize a user-centered design approach involving end users in the development process. Ajaykumar and Huang (2020) conducted a user case study on the problems that arise in the programming process of a robot task using a robot programming interface through user demonstration. In a study by Elprama et al. (2017), two workers were interviewed to identify recommendations for improving the collaboration between robots and human workers. Workers acknowledged the reduction in mental and physical workload owing to the introduction of collaborative robots, and remarked that collaborative robots should adapt the way they assist based on the characteristics of human workers. Tihay and Perrin (2018) conducted a survey of French industrial representatives to identify the main requirements for HRC. The participants mentioned the importance of the ease of maintenance tasks and the integration of the robot cells. Kildal et al. (2018) demonstrated a collaborative robot for students in vocational training and industry professionals classified as potential users of collaborative robots. They analyzed their expectations and concerns regarding the system. Aaltonen and Salmi (2019) used an online questionnaire to determine the challenges and development needs of collaborative robots from various respondents, such as robot manufacturers, distributors, system integrators, industry, and academia. An industry report by Bauer et al. (2016) surveyed companies that adopted collaborative robots and confirmed operational efficiencies or improved worker experience. The ROBOFOOT project by Maurtua et al. (2012) identified user requirements for developing various solutions to introduce robotics to the traditional shoe manufacturing industry. Adamides et al. (2014) obtained a set of guidelines for human–computer interaction and HRI professionals for designing teleoperation robots and grouped them into eight categories. Sawai et al. (2017) proposed an approach to describe the interaction between the architectural design aspects used in industrial robots and user requirements.

These terminology sets were redefined or integrated to consider the terminology for user needs described in several studies. Table 1

TABLE 1 User requirements of collaborative robots.

User requirements	Definition	Reference
Pleasurable		
Worker adaptability	The robot should be able to adapt to the behavior of individual workers.	CoLLaboratE Project (2020); Elprama et al. (2017)
Independence	Collaborative robots should be able to identify the optimal task independently.	CoLLaboratE Project (2020)
Usable		
Accessibility	The robot should be easily accessible to the human operator at all times.	CoLLaboratE Project (2020)
Manual switching on error	The operator should be able to take over the robot's processes, if the robot breaks down.	CoLLaboratE Project (2020)
Flexibility	The robot should be flexible and adaptable to various tasks.	Maurtua et al. (2012); Adamides et al. (2014); Aaltonen and Salmi (2019); Bauer et al. (2016); Sawai et al. (2017); Tihay and Perrin (2018)
Learnability	The robot should be easy to use for all levels of operators' experience.	Aaltonen & Salmi (2019); CoLLaboratE Project (2020); Kildal et al. (2018)
Ease of maintenance	The maintenance and repair management of the robot should be easy (cleaning, process, monitoring).	Bauer et al. (2016); CoLLaboratE Project (2020); Maurtua et al. (2012); Sawai et al. (2017); Tihay and Perrin (2018)
Optimal task allocation	Optimal task allocation should be made between robots and humans (operator).	Aaltonen and Salmi (2019); Bauer et al. (2016)
Ease of interaction	Collaborative robots should interact with the user easily and naturally.	Adamides et al. (2014); CoLLaboratE Project (2020); Elprama et al. (2017)
Fast programming	The robot should be able to be reconfigured/ reprogrammed quickly even by inexperienced users.	Aaltonen and Salmi (2019); Ajaykumar and Huang (2020); Bauer et al. (2016); CoLLaboratE Project (2020)
Improved ergonomics	The robot should reduce the burden on the human operator in terms of physical and mental workload.	Adamides et al. (2014); Aaltonen and Salmi (2019); Bauer et al. (2016); CoLLaboratE Project (2020); Tihay and Perrin (2018)
Reliable		
Stop/slow for human recognition	The robot should stop or slow down depending on the distance from the operator for safety.	Bauer et al. (2016); Kildal et al. (2018); Sawai et al. (2017)
Safe contact	Physical contact between the human operator and the robot must be possible under safe conditions.	CoLLaboratE Project (2020)
Force regulation	The force of the robot should be regulated so that it does not pose a threat to the operator.	Bauer et al. (2016)
Error prevention	Errors that may occur in the operation of the robot should be prevented in advance.	Adamides et al. (2014)
Durability	The robot should be robust to the external environment.	Sawai et al. (2017)
Life expectancy	The robot should have a sufficient life expectancy.	CoLLaboratE Project (2020)
Functional		
Payload capacity	The robot should be able to handle heavy payloads.	CoLLaboratE Project (2020)
Work stability	The robot should be able to perform the task without a human operator in a stable manner.	CoLLaboratE Project (2020); Maurtua et al. (2012); Sawai et al. (2017)
Battery performance	The robot battery should be able to be recharged quickly.	Aaltonen and Salmi (2019); CoLLaboratE Project (2020)
Operating time	The robot should provide a long operating time.	CoLLaboratE Project (2020)

provides the definitions of the user requirements, categorized based on the literature.

The user requirements categorized by functionality include factors related to the ability to perform tasks. Task performance is a fundamental requirement of collaborative robots. Payload capacity, which refers to the maximum weight a collaborative robot can carry in a work situation, is a critical factor in industries that handle heavy materials, such as construction and manufacturing. Work stability refers to the ability of the robot to perform activities precisely and consistently. Work stability is critical in industries in which precision and accuracy are essential. Battery performance refers to the time required to recharge a collaborative robot, and is pivotal to its overall performance. A shorter recharge time allows the collaborative robot to operate for extended periods without interruption, which can enhance task performance. The operating time refers to the total amount of time that a collaborative robot can operate before it must be recharged. Collaborative robots with long operating hours can reduce maintenance costs and boost productivity at the workplace.

The reliability of collaborative robots is crucial to ensure safe and efficient work for human workers. The most evident way to ensure reliability is to ensure the safety of human workers. Stop/slow for human recognition is a factor that monitors the distance between the human worker and the robot in real time when the human worker enters the robot's workspace and safely stops or slows down when contact is possible. This is essential for preventing accidents and ensuring worker safety. Unless collaborative robots are fully automated, human workers must physically interact with them for maintenance or programming, even when they are not in a collaborative situation. Therefore, safe contact is a vital reliability factor. In addition, the force regulation factor can regulate the amount of force that a robot applies when interacting with an object or person to prevent worker injury and ensure safety. Error prevention is a factor that prevents errors that may occur when a robot performs a task. A collaborative robot prone to control errors is a major source of unreliability for workers. Durability is a fundamental factor related to the reliability of collaborative robots. Collaborative robots are designed to withstand harsh working conditions, such as temperature, humidity, and dust, reducing the need for maintenance and repair and keeping the workplace safe and productive. Collaborative robots with a long-life expectancy can provide years of reliable service, thereby reducing the need for replacement.

In contrast to traditional industrial robots, collaborative robots are designed to work alongside human workers. Hence, several usability factors need to be considered when implementing collaborative robots in a work cell. Accessibility is an important usability factor for collaborative robots. Collaboration can be facilitated, and productivity can be improved by using a collaborative robot that is easily accessible and usable anytime and anywhere. The manual switching on error was also identified as a factor in terms of usability. In the case of an error or emergency, workers must take over the work process from the collaborative robots. In contrast, collaborative robots can assist workers in taking charge of the situation quickly and safely, thereby minimizing downtime. Flexible collaborative robots that can be easily integrated into existing work cells are essential for improving efficiency and productivity. Flexible collaborative robots reduce the need for extensive work cell reconfiguration. In addition, collaborative robots that are easy to learn make it quick and easy for workers to learn how to use and interact with them. In particular, an easy-to-learn collaborative robot can improve work efficiency by bridging the gap between workers with different task proficiency levels. It has been confirmed that several workers prefer simple maintenance in terms of management. Collaborative robots with easily replaceable parts and simple maintenance procedures can save time and money in the long term. Optimal task allocation to compensate for weaknesses and maximize the strengths of human workers and collaborative robots can improve overall work efficiency. A collaborative robot that enables apparent interactions through an intuitive user interface is essential at the usability level. Easy interaction can be achieved through multiple modalities, such as voice and gestures. Collaborative robots should consider the work environment, conditions, and constraints that may arise between interactions. Ergonomically improved collaborative robots can reduce the musculoskeletal and cognitive strains of tasks and improve task efficiency.

Finally, among the several requirements of collaborative robots, the user-friendliness factor was categorized as “pleasurable.” Collaborative robots can operate alongside human workers, offering assistance and support as required, which is a key benefit. To accomplish this, they must interact with different types of workers and adjust their work styles. In particular, collaborative robots should be able to adapt continuously to the pace and language of each worker, which can be a significant advantage for workers who are not accustomed to using robotic technology. Another essential factor to consider is independence. Rather than acting on human commands or programmed logic, the robot must assess the current work situation and independently identify the optimal task. These factors, which prioritize worker-friendly interactions rather than task productivity and efficiency, can significantly impact the adoption and trust in collaborative robotics technology, leading to an improved work environment and motivation. Therefore, to ensure the quality of collaborative robots, an architecture should be in place to measure and evaluate the quality based on the user requirements mentioned in this section.

3.2 | Review of assessment standards for collaborative robots

This section comprehensively reviews the process of establishing and revising existing quality standards for collaborative robots. The characteristics of each quality standard were identified by analyzing and comparing various standard clauses applicable to collaborative robots, such as the performance evaluation for industrial robots and operation requirements for collaborative robots, as well as service robot test methods and interactive system design guidelines. In addition, this study considered the standard clauses applicable to general robot arms rather than mobile platforms or wearable robots. The timeline for the development of applicable evaluation standards from the first to the latest revisions is shown in Figure 3. The criteria for evaluating the performance of robots were first established in ISO 9283, which consists of criteria for evaluating the performance according to the automation of industrial robots. Following ISO 13855, published in 2002 and 2010, the calculation of stopping distances and safety requirements for human approaches in human-involved industrial environments and the establishment of operation requirements for collaborative robots were introduced. In line with the evolution of human needs, the early standards for industrial robots mainly considered aspects of functionality. As the level of coexistence was reached, the standards primarily addressed safety requirements for human–robot contact. However, usability has only recently been briefly addressed for service robots.

Table 2 lists the contents of the latest editions of the ISO standard for safety requirements for collaborative robots, control system evaluation methods, and interactive system design guidelines. Collaborative robot technology levels and description levels are categorized according to the characteristics and contents of the items presented in the standard clauses.

The analysis of the standard clause was divided into three levels according to the content specified in the standard clause. For example, a clause outlining the items or characteristics that should be considered to satisfy the quality is designated as a principle. Clauses that specify the minimum levels and requirements necessary to ensure quality are designated as guidelines. Finally, if a clause specifies the conditions and procedures for evaluation and can be measured quantitatively through relative or absolute metrics, it is designated as a standard.

ISO 9283 was established in 1990 as a standard for evaluating robotic manipulation performance. The first edition of ISO 9283 has several drawbacks, including an inability to specify standard test paths and loads. The robots' workspaces and load ratings were not identical, making a relative comparison between the two robots difficult. Accordingly, it was revised to specify the test paths and objectively measure the performance characteristics under the same conditions. ISO 9283 is the international standard for the performance evaluation of industrial robots. The performance of most industrial robots is verified through an evaluation method, and the performance of collaborative robots conforms to ISO 9283 (International Organization for Standardization, 1998; Slamani et al., 2012). This standard corresponds to "no coexistence" as a metric for measuring work performance according to the automation of industrial robots. Clause 7 of ISO 9283 describes the evaluation of robot pose characteristics. The pose characteristics refer to the ability of a robot to move and stop accurately (Slamani et al., 2015). The clause measures pose characteristics through various evaluation methods, such as pose, distance accuracy and repeatability, position stabilization time, position overshoot, and drift (Kumičáková et al., 2016; Pollák et al., 2020; Slamani et al., 2015). In particular, clause 7.2 provides a standardized method for measuring and evaluating pose accuracy and repeatability. The evaluation involves moving the robotic manipulator to a predefined position and

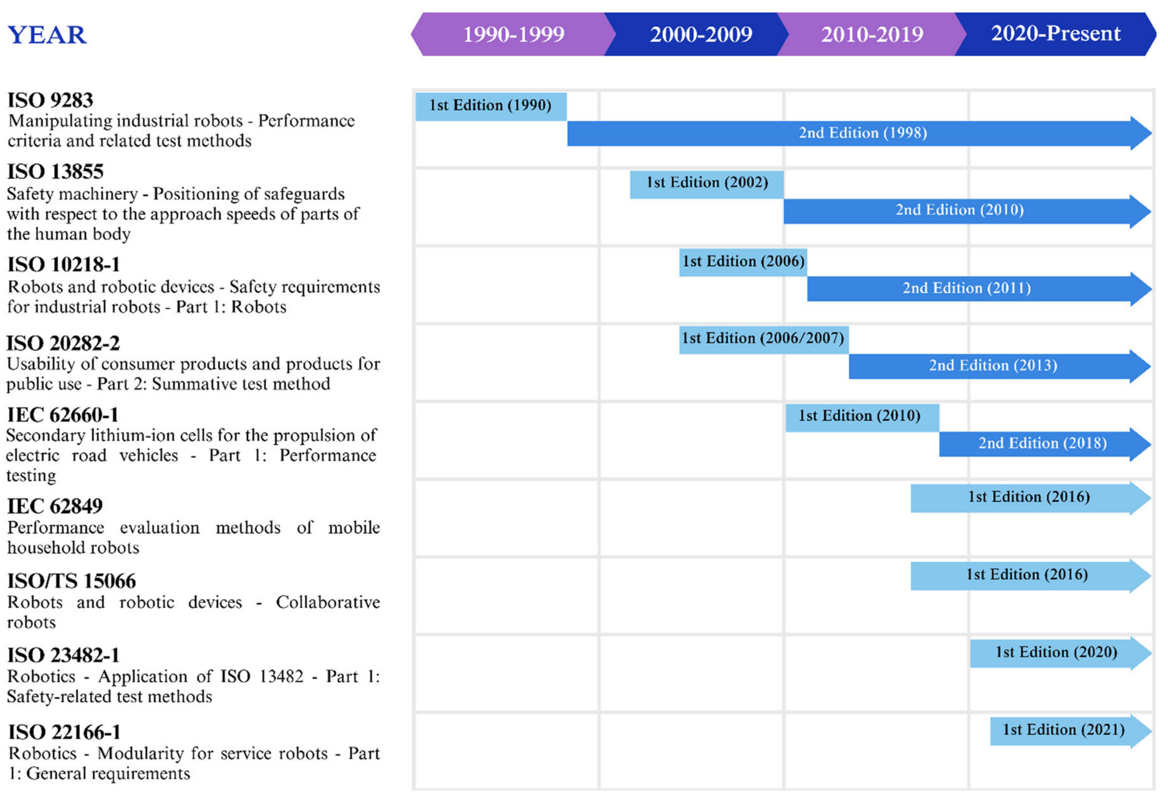

FIGURE 3 Process of establishing/revising standards applicable to collaborative robots.

TABLE 2 Quality standard clauses for collaborative robots.

No.	Category	Description	Description level	Technology level
ISO 9283, Manipulating industrial robots—Performance criteria and related test methods	Pose characteristics test	Introduces a procedure for evaluating the ability of an industrial manipulating robot to move to a specified position and orientation accurately and repeatedly. In this clause, the new position is measured by calculating the deviation between the programmed command position and orientation as well as the actual position and orientation of the robot.	Standard	No coexistence
	Path characteristics test	Provides guidelines on measuring the robot's path accuracy and repeatability. It measures how well the robot's actual movements match the intended movements, and how consistent the robot's movements are when performing the same task multiple times.	Standard	No coexistence
ISO 13855, Safety of machinery—Positioning of safeguards with respect to the approach speeds of parts of the human body	Calculation of stopping performance and minimum distance	ISO 13855 Clause 5 provides a method for calculating the stopping performance and distance of the entire system. The stopping performance is measured by including the operating time of the protective equipment and the response time of the control system.	Standard	Coexistence
	Calculation of minimum distance for electronic detection devices	Specifies the main requirements according to the approach direction of a person or a part of the human body. Provides a method for calculating the minimum distance in various situations of human approach through electronic detection.	Standard	Coexistence
ISO 10218-1, Robots and robotic devices-Safety Requirements for industrial Robots-Part 1: Robots	Safety-related control system performance	Provides procedures for evaluating the safety-related performance levels of the control systems. For error prevention through verification, the control system shall demonstrate that the performance requirements of the safety requirements standard provided in this clause are met.	Standard	No coexistence
ISO/TS 20282-2, Usability of consumer products and products for public use—Part 2: Summative test method	Usability testing of consumer products and products for public use	ISO/TS 20282-2 introduces a comprehensive test procedure for the ease of operation of products. In particular, it provides a guideline for the evaluation of the general usability of a product or system, including efficiency, effectiveness, and satisfaction.	Principle	No coexistence
IEC 62660-1, Secondary lithium-ion cells for the propulsion of electric road vehicle—Part 1: Performance testing	Secondary battery-specific requirements testing	The standard introduces a performance evaluation procedure for secondary lithium-ion batteries used as driving power sources for electric vehicles. The performance evaluation procedures for batteries described in this clause, such as energy efficiency and cycle life tests, are partially applicable to systems using secondary batteries.	Standard	No coexistence
IEC 62849, Performance evaluation methods of mobile household robots	Operation time per single charge	IEC 62849 describes the procedures for the performance evaluation of household mobile robots. Clause 8 provides the test procedures for the operating time of a robot per single charge.	Standard	No coexistence

TABLE 2 (Continued)

No.	Category	Description	Description level	Technology level
ISO/TS 15066, Robots and robotic devices-Collaborative robots	Safety-rated monitored stop	Provides robot system requirements for a safety-rated monitoring stop, whereby the robot stops its work activity upon recognizing a human within the collaborative area.	Guideline	Coexistence
	Hand guiding	Hand guiding refers to the transmission of commands from a human operator to a robotic system through a hand actuation device. This clause provides guidance on the safety requirements for the hand guiding process.	Guideline	Cooperation/collaboration
	Speed and separation monitoring	This type of operation allows the robot system and the human operator to move simultaneously in a collaborative workspace. Provides speed and separation sensing guidelines for maintaining a protective separation distance between the robot and the human operator in the collaborative work area.	Guideline	Cooperation/collaboration
	Power and force limiting	Describes the power and force limitation requirements for safety measures resulting from intentional and unintentional physical contact between the robot and the human operator.	Guideline	Cooperation/collaboration
ISO/TR 23482-1, Robotics-Application of ISO 13482-Part 1: Safety-related test methods	Test of physical hazard characteristics	Clause 6 of ISO/TS 23482-1 focuses on the physical hazard characteristics of personal assistance robots and provides guidance on tests that can be performed to assess these characteristics.	Standard	No coexistence
	Test of endurance characteristics	This clause provides a test procedure for damage to personal assistance robots to verify their durability over the design lifetime. The goal of the tests is to evaluate the robot's ability to operate and store under various environmental conditions.	Standard	No coexistence
	Testing of safety-related control functions	Presents a test procedure for evaluating the performance of safety-related controls. Consists of items to evaluate the object identification ability and electromagnetic immunity of electrosensitive protective equipment in various environments.	Standard	Coexistence
	Test of reliability of autonomous decisions and actions	Provides guidance for evaluating the reliability of a robot's autonomous decisions or actions. This clause measures the robot's object recognition response to assess whether it is performed correctly.	Principle	Cooperation/collaboration
ISO 22166-1, Robotics-Modularity for service robots-Part 1: General requirements	Robot Modularization-Guidance for testing robot modules	ISO 22166 Annex. D.4 introduces the evaluation methods for the performance conformance testing of service robot modules. This annex outlines the methods for evaluating the overall quality of robot modules, including mechanical performance testing, electrical performance, and usability testing.	Principle	No coexistence

orientation, and then measuring the deviation from the expected pose characteristics (Pagani et al., 2021; Slamani et al., 2015). As such, ISO 9283 describes the experimental conditions and environments for characterizing the pose path of a robot and specifies the experimental procedures and measurement metrics. This clause provides a standard-level description because relative comparisons can be made through evaluations based on the procedures specified in the standard.

ISO 13855 was established as a standard for positioning protective devices based on the approach speed of the body parts when a human approaches a robot. ISO 13855 provides guidance on the positioning of safeguards in relation to the approach speed of the human body parts (International Organization for Standardization, 2010). The second edition expands the scope of the human body to include not only the hands/arms but also the positioning of restraints concerning the approach speed of different body parts. It considers the required safety distance when using restraints, in conjunction with the possibility of bypassing the detection zone. Clause 5 of ISO 13855 describes the requirements for the stopping performance of the machine safeguards. The minimum stopping distance must be calculated to ensure that the stopping performance of a safeguard satisfies the required standards (Valori et al., 2021). The calculation of the minimum stopping distance considers several factors including the approach speed of the body part, the reaction time of the system, and braking performance (Belingardi et al., 2017; Marvel & Norcross, 2017; Szabo et al., 2012). Clause 6 of ISO 13855 provides guidelines for calculating the minimum distances for electronically detectable guards. Electrosensitive protective equipment (ESPE) detects the presence of a worker in the hazardous area of a machine through sensors and triggers a safety device to prevent injury or danger (Gualtieri et al., 2018; Marvel & Norcross, 2017). This section provides specific formulas for calculating the detection capability of ESPE sensors, their reaction time, and the minimum distance based on the direction of approach of the body part. Consequently, ISO 13855 can be perceived as a clause on the safety distance required when a worker approaches a robot in a collaborative situation at the coexistence level. It provides standard-level information because the stopping performance of the protective device can be quantitatively measured according to the stopping distance formula.

The standard for the safety requirements of industrial collaborative robots was established in 2006 under ISO 10218-1. The second edition provides more detailed requirements for ensuring worker safety, including the performance criteria for safety control systems and collaborative operations. As the operational requirements for collaborative robots are covered in more detail in ISO/TS 15066, ISO 10218-1 primarily reviews clauses related to the performance of safety-related control systems. Clause 5.4 of ISO 10218-1 specifies the level of performance required to fulfill the safety functions of the control system (International Organization for Standardization, 2011). ISO 13849-1 (International Organization for Standardization, 2015) and ISO 13849-2 (International Organization for Standardization, 2012) provide more detailed procedures for evaluating and verifying the performance of safety-related control systems. As the safety performance of a control system is not related to its collaborative characteristics, it is an item to be satisfied at the "no coexistence" level; it is classified as a standard level because it presents different performance criteria to be satisfied depending on the characteristics of the control system and provides a measurable evaluation method.

ISO/TS 20282-2 outlines a test method for evaluating the usability of a product or system (International Organization for Standardization, 2013). Clause 7 specifies the purpose and scope of the test, the evaluation environment, and the method for measuring the achievement of the purpose. The effectiveness, efficiency, and satisfaction with the human use of a product to achieve its intended purpose were evaluated based on objective and subjective measures. The objective measures included success rate, work time, cost, and cognitive/physical effort, whereas the subjective measures included perceived satisfaction. However, only the conceptual definitions and characteristics of the items that constitute usability have been presented, with no evaluation procedures or criteria that can be measured quantitatively. Therefore, the ISO/TS 20282-2 description level is categorized as a principle at the "no coexistence" level because it is not a usability principle for collaborative robots, but a usability principle for daily products that do not specify a system.

IEC 62660-1 clause 7 describes the evaluation of the performance of secondary lithium-ion batteries used as the driving power sources for electric or hybrid vehicles (International Electrotechnical Commission, 2018). This clause provides a method for calculating the storage life, cycle life, and energy efficiency by measuring the current loss generated during discharge and charging, which can be utilized for evaluating the battery performance of collaborative robots (Brivio et al., 2017; Zhou et al., 2022). The assessment clause related to the battery performance of the robot should be measurable regardless of the collaboration level; hence, it is categorized as "no coexistence." The description level is categorized as a standard because it provides the test methods and metrics for battery performance assessment.

Clause 8 of IEC 62849 introduces a method for evaluating household mobile robot operating time per charge (International Electrotechnical Commission, 2016). The maximum operating time of the robot per charge cycle was estimated. The total operating time was calculated by recording the total energy input from a fully charged state, and the operating time and energy consumption until the robot stopped working or could not be restarted (Huang et al., 2022). As the evaluation of operating time presented in this clause should be applicable to all levels of collaboration, the technology level can be categorized as "no coexistence," and provides information at the standard level, as it enables a quantitative evaluation of the conditions and energy consumption for the operating time.

ISO/TS 15066 is a technical specification standard describing collaborative robot safety requirements (International Organization for Standardization, 2016). This standard defines the different types of collaboration that can occur between humans and collaborative robots, and the safety requirements in collaborative scenarios.

ISO/TS 15066 distinguishes between four types of collaborative operations: safety-rated monitored stop (SMS), hand guiding (HG), speed and separation monitoring (SSM), and power and force limiting (PFL). SMS is the simplest collaborative operation type (Vicentini, 2020). ISO/TS 15066 clause 5.5.2 proposes requirements for designing collaborative robots to cease movement when they detect the presence of a human in the collaborative workspace. A collaborative workspace should be configured at a distance that satisfies the ISO 13855 requirements. To assess the reliability of SMS, the collaborative robot should accurately detect the presence of a human and automatically restart when the human leaves the collaborative workspace (Belingardi et al., 2017; Malm et al., 2019; Marvel & Norcross, 2017). HG, the second level of collaborative operation, allows a human operator to easily guide and program the movements of a collaborative robot (Belingardi et al., 2017; Safeea & Neto, 2022; Vicentini, 2020). Before the human operator enters the collaborative workspace, the robotic system must generate the SMS and prepare for HG (Chemweno et al., 2020). When an HG device controls the robot, the SMS is disabled and the HG operation is performed. The robot system must activate the SMS again when the operator releases the guiding device and resume work when the operator leaves the collaborative work area (Karagiannis et al., 2022). The third level of collaborative operation, SSM, enables the collaborative robot and human operator to work in close proximity. At this level, the collaborative robot must monitor its speed and distance from the human operator, and apply its SSM function to ensure a safe distance (Belingardi et al., 2017; Michalos et al., 2018; Vicentini, 2020). Clause 5.5.4 provides a method for calculating the protective separation distance based on the change in the position of the human operator and the reaction time and stopping performance of the robot. Clause 5.5.5 PFL describes the robot system requirements for intentional/unintentional physical contact situations. The clause specifies that to account for potential contact between robots and human operators, the range of forces and pressures allowed for contact should be regulated according to the body parts (Chemweno et al., 2020; Gleirscher et al., 2022; Michalos et al., 2018; Vicentini, 2020). However, the majority of the content described in ISO/TS 15066 is designated as a guideline because it presents the requirements and conditions for ensuring safety rather than specifying its assessment method. In the four types of collaborative operations, SMS is an essential function at the coexistence level, whereas HG, SSM, and PFL specify safety requirements in collaborative situations of cooperation/collaboration.

ISO/TR 23482-1 (International Organization for Standardization, 2020) is a technical report that provides guidance on safety-related test methods for personal-assistance robots based on the international standard ISO 13482 (International Organization for Standardization, 2014). Clause 6 of ISO/TR 23482-1 addresses the testing for three main physical hazards. This section describes a safety assessment method for the physical hazards of robots, which is equivalent to no coexistence, and provides information on standard-level principles, experimental apparatus, and procedures for assessing the risk of voltage in user-accessible parts, the risk of acoustic noise, and the risk of surface temperature (Valori et al., 2021). Clause 9 introduces a risk test procedure for assessing the durability characteristics of robots. The assessment of the durability characteristics of the robot is a requirement for no coexistence. At the standard level, this clause specifies how to evaluate a robot's durability under certain environmental circumstances, such as varying temperature and humidity, and its robustness to external or inappropriate impacts. Clause 14 specifies the evaluation of the safety-related control functions. This clause is required for coexistence and provides standard-level information because it covers the methods and conditions for evaluating the ability of electrosensitive equipment to recognize objects reasonably in different environments. Clause 17 of ISO 23482-1 states that trust in a robot's autonomous decisions or actions should be evaluated, indicating that this is required at the cooperation/collaboration level. However, while the clause mentions the need to assess a robot's autonomous decisions and actions, the clause content only outlines the procedures for evaluating the object recognition by the robot system. Therefore, the clause can be classified as a principle.

ISO 22166-1 provides requirements and guidelines for modularizing service robots in various environments. Annex. D.4 presents the methods for testing the performance conformance of the robot modules (International Organization for Standardization, 2021). This section outlines the methods for various evaluations of robot modules, such as structural performance, electrical performance, software testing, and environmental and usability testing, regardless of the robot's collaboration level. However, it does not specify the procedures for testing and simply provides principle-level guidance that should be addressed during the testing process (International Organization for Standardization, 2021; Zou et al., 2022).

3.3 | Correlation matrix

In this section, the matrix determines whether the existing quality metrics reviewed in Section 3.2 satisfy the identified user requirements. Figure 4 shows the overall correlation matrix.

We identified several assessment methods to consider the user requirements related to the functionality and performance of a collaborative robot. As illustrated in Figure 4, most user requirements belonging to functionality are presented with evaluation clauses at the standard level. Battery performance and operating time are significant work performance metrics related to performance test methods for secondary batteries and the assessment of the robot's maximum operational time per single charge cycle. These standards describe the test methods for electric vehicles and service robots, but not for industrial collaborative robots. Nonetheless, the assessment methods should be applicable to industrial collaborative robots with some modifications. The methodology for evaluating work stability is mapped to the assessment of pose and path characteristics in ISO 9283. The testing of pose and path characteristics in ISO 9283 provides a method for evaluating the reliability of a robot that manipulates programmed actions. However, as the standard provides

		ISO 9283		ISO 13855		ISO 10218-1	ISO/TS 20282-2	IEC 62660-1	IEC 62849	ISO/TS 15066				ISO/TR 23482-1				ISO 22166-1
		Pose characteristics test	Path characteristics test	Calculation of stopping performance and minimum distance	Calculation of minimum distance for electronic detection devices	Safety-related control system performance	Usability testing of consumer products and products for public use	Secondary battery specific requirements testing	Operation time per single charge	Safety-rated monitored stop	Hand guiding	Speed and separation monitoring	Power and force limiting	Test of physical hazard characteristics	Test of endurance characteristics	Testing of safety-related control functions	Test of reliability of autonomous decisions and actions	Robot Modularization-Guidance for testing robot modules
Technology Level		No coex	No coex	Coex	Coex	No coex	No coex	No coex	No coex	Coex	Coop/Coll	Coop/Coll	Coop/Coll	No coex	No coex	Coex	Coop/Coll	No coex
Pleasurable	Worker Adaptability																	
	Independence																Principle	
Usable	Accessibility						Principle											
	Manual Switching on Error																	
	Flexibility																	
	Learnability																	
	Ease of Maintenance																	
	Optimal Task Allocation																	
	Ease of Interaction						Principle											Principle
	Fast Programming																	
	Improved Ergonomics						Principle											
Reliable	Stop/Slow for Human Recognition			Standard	Standard					Guideline		Guideline				Standard		
	Safe Contact			Standard							Guideline			Standard				
	Force Regulation												Guideline					
	Error Prevention					Standard										Standard		
	Durability														Standard			Principle
	Life Expectancy																	
Functional	Payload Capacity																	Principle
	Work Stability	Standard	Standard															
	Battery Performance							Standard										Principle
	Operating Time								Standard									

FIGURE 4 Correlation matrix for user requirement and collaborative robot standard clauses.

the measurement methods and conditions, the measured results allow for relative comparisons with other robotic systems but do not provide absolute criteria for gauging user experience quality. The payload capacity is one of the most important characteristics of a collaborative robot because it indicates the tasks and capabilities that the robot can handle. The payload capacity was assigned to the assessment criteria for the mechanical performance in ISO 22166-1 because it corresponds to the mechanical assessment criteria for collaborative robots.

User requirements for the reliability of a robot are most often considered in the existing standards. No metrics were observed to evaluate the life expectancies of robots. The user requirements for the durability of a robot are directly related to the durability assessment criteria, which can be assessed through durability tests for external impacts and environmental conditions, as described in ISO 23482-1 clause 9. The user requirements for error prevention were mapped to the safety-related performance levels of the control system in ISO 10218-1. It is possible to measure quantitatively whether an error can be prevented in advance and does not lead to a major loss of function, according to the performance level evaluation items of the safety-related control system. User requirements for force regulation are linked to the PFL of ISO/TS 15066, which describes the robot's force and power limits for human safety. Users want to be assured of their safety if they need to contact a robot or an unexpected contact situation occurs. Different evaluation methods should be provided, as contact with a robot can occur in several scenarios, such as with an HG, a handover, or unexpected contact. According to the direct contact between robots and human body parts, the ISO 13855 and ISO/TS 15066 requirements for HG, which contain items to assess safety in such contact situations, have been mapped to ISO/TR 23482-1 clause 6, characterization of hazards in physical contact. ISO 23482-1 defines the test items for evaluating physical hazards in contact situations, such as voltage and acoustics. Furthermore, the stopping performance of the robot when approaching contact can be included as an item to evaluate safe contact. "Stop/slow for human recognition" is considered in several standards because it is directly related to the safety of collaborative robot operators. The "stop/slow standards for human recognition" are generally divided into two categories. The first is to assess the ability to recognize the human body or the entire body, which can be evaluated by measuring the human recognition ability of electronic sensing equipment under various environmental conditions on a test specimen similar to the human body. The second is the evaluation of the stopping and slowing performances. The formula for calculating the minimum distance of the ESPE enables a pass/fail judgment of the stopping and slowing performance of the collaborative robot. Therefore, the relevant assessment criteria ISO/TR 23482-1 clause 14, SMS and SSM of ISO/TS 15066, and ISO 13855 requirements for the minimum distance between humans and robots were assigned to this user requirement.

According to the results shown in Figure 4, there are no standards for evaluating natural or user-friendly interactions with robots, such as “usability” or “pleasurable.” Regarding usability, ISO/TS 20282-2 describes some assessment principles related to task effectiveness and efficiency, such as enhancing the accessibility, interaction, and ergonomics of daily products. However, they are unsuitable for applications in collaborative robotic systems. In addition to these outlined principles, no evaluation metrics that satisfy the user requirements for usability can be found.

Worker adaptability and independence are factors that enable user-friendly interactions but have not yet been considered in assessment standards. Although clause 17 in ISO/TS 23482-1, reliability of autonomous decisions and actions of robots, is linked to independence as a user requirement and cites the necessity for assessment, the actual clause only outlines procedures for evaluating the object recognition of robotic systems. Other items related to “pleasurable” are not identified in the standards.

4 | DISCUSSION

4.1 | Quality standards for user-centered design

By classifying the standards for collaborative robots according to identified user requirements, this study aims to identify the limitations of the existing quality standard system and establish a direction to fill the gap between user requirements and standards. A literature review yielded 21 user requirements, and a correlation matrix was derived by reviewing the standards applicable to collaborative robots. The results of this study were extracted from previous research findings and considered only some of the user requirements; however, it is adequate to demonstrate that the existing quality assessment standards do not consider user requirements.

Standards for collaborative robots begin with those for evaluating the performance of industrial robots at the No coexistence level and continue to be primarily concerned with ensuring human safety at the Coexistence level, where humans are involved. Most standards related to safety and reliability provide standard-level evaluation procedures and criteria at the no coexistence or coexistence levels. In contrast, only the guidelines for safety requirements are presented at the cooperation level and above. To reflect technological advancements, a system that can assess the quality of collaborative robots in collaboration scenarios at the cooperative level is required. For instance, the evaluation criteria for coexistence and cooperation may differ when monitoring the speed and distance between a human operator and a robot. Therefore, it is necessary to distinguish between these technical levels and establish metrics to measure them. The quality standards corresponding to functional and reliable are thoroughly addressed, including detailed testing procedures and environmental considerations. While a significant number of user requirements fall within the usable and pleasurable categories, their evaluation often relies solely on existing design principles or overlooks them entirely.

Several studies have discussed the dynamic characteristics of user requirements as technology evolves (Chowdhury et al., 2020; Wang & Yu, 2016). These quality attributes should be addressed, as they are likely to evolve into more important user needs in the future according to changes in the level of needs. Therefore, quality standards should consider the interaction factors between human workers and robots. Users want to take over the process of the robot quickly so that the entire work cell does not stop when a robot error occurs; however, standards do not consider this characteristic. A robot that can easily and flexibly adapt to various tasks is an essential user requirement in several studies, and a method for its evaluation is required. A related standard, ISO 10218-2 safety requirements for the maintenance of industrial robotic systems, does not have an item for assessing the ease of maintenance but provides safety requirements during maintenance. However, while safety in maintenance is an essential factor to consider, there is a need for further consideration of items that can measure and evaluate the ease of maintenance based on user requirements. The efficient allocation of tasks between human workers and collaborative robots is also an important consideration. Several studies have been conducted on optimal task allocation (Kwon & Suh, 2014; Schoen et al., 2020; Tsarouchi et al., 2017). Optimal task allocation can affect task efficiency because human workers have the advantage of being flexible and creative, whereas robots have the advantage of being able to perform repetitive and precise tasks. Technological advances have made flexible interactions with collaborative robots increasingly diverse and complex. Recently, increasing efforts have been made to overcome the limitations of interaction by combining various modalities, such as voice, gesture recognition, and extended reality technology (Dallel et al., 2023; Panagou et al., 2022; Strazdas et al., 2022). Therefore, it is necessary to develop modality-specific quality criteria and evaluate whether the interaction is successful in various environmental settings. Based on the identified requirements, users want to be able to instruct the robot to perform a task without any prior knowledge of the collaborative robot. While several recent studies have discussed this issue (Ajaykumar & Huang, 2020), there has been no research on metrics to evaluate the ease of programming. Improved ergonomics is considered a metric that can evaluate work efficiency, and metrics in this area should be developed to measure the extent to which collaborative work reduces the physical and cognitive loads of workers.

This paper analyzes the quality standards of industrial collaborative robots based on a user-centered design framework, highlighting the need to give more importance to considering user requirements during the design and development of collaborative robotic systems. It was identified that quality standards needed to be re-established to shift the paradigm from system-centered design to user-centered design. The results of this study can be used in conjunction with various methodologies to evaluate the performance, safety, and usability of robots for efficient HRI (Bethel et al., 2007; Chacón et al., 2021). It is also expected to serve as a basis for designing and developing collaborative robots for human-centered manufacturing, a core value of Industry 5.0.

4.2 | Limitations and further research

This study aims to provide information on the quality attributes of collaborative robots that are not considered by the existing quality standard system by categorizing standard provisions for collaborative robots according to derived user requirements. The results of the study examined the level of user requirements reflected in existing quality standards but did not analyze how the considered user requirements are connected and structured with quality.

The first step for future research to develop quality standards that can reflect user needs is to identify and structure quality factors to assess whether user needs are fulfilled. Quality of Experience (QoE) is often mentioned as a metric to measure the degree to which user needs are fulfilled (Crespi et al., 2011; De Marez & De Moor, 2007; Mahmud et al., 2019). However, research on measuring and defining QoE is mainly limited to the field of telecommunication or multimedia (Banjanin et al., 2022; Baraković et al., 2010; Rehman Laghari & Connelly, 2012). Consideration of QoE needs to be extended to various domains to fulfill the user needs during the technology development process (Mitra et al., 2013). Since QoE has a multidimensional characteristic, defining the factors that constitute QoE through user requirements is necessary. The user requirements considered in this study were based on a review of prior literature that identified user needs through various approaches, such as demonstrations and surveys, and may not consider newly expressed user requirements. Traditional engineering methodologies have limitations for new technologies, such as collaborative robots, where user experience has not been sufficiently accumulated, and analytical techniques such as text mining are needed to overcome this (Qureshi et al., 2021; Soni et al., 2020). This study does not calculate weights that can reflect dynamic user requirements in the context of technological advancement. Due to social trends and technological advancements, new longitudinal methodologies that can reflect relative weights are required to account for dynamic user requirements. Once the conceptual definition of QoE is established, it is planned to establish a system for subjective/objective evaluation by linking user and system requirements.

QoE can be influenced by human characteristics, including cognitive and psychological aspects of the user (Crespi et al., 2011; Mitra et al., 2013). In addition to the user's human characteristics, it is necessary to reflect the effect of moderating variables that influence the parameters to define the experience quality because it is changed by various influencing factors such as system characteristics of the technology and usage context characteristics (Li et al., 2015; Shin, 2017). Through this process, it is expected that we can identify common attributes of user needs that appear when introducing new technologies, and thus confirm their generalizability to the QoE evaluation of new technologies including collaborative robots.

5 | CONCLUSION

In this study, the limitations of the existing quality standard system were identified by defining the user requirements and reviewing the standard clauses for collaborative robots according to a user-centered design framework. We derived a correlation matrix between 21 user requirements and collaborative robot quality standards and discovered a significant gap between the two factors. Functionality was assigned as an indicator to evaluate the robot's task performance, whereas reliability was primarily a safety-related quality attribute. In terms of "usability" and "pleasurable," user requirements related to natural or user-friendly interactions between the user and the collaborative robot were identified. Nonetheless, most standards associated with collaborative robots, starting with quality assessment methods for performance and function, are utilized to ensure human safety. The literature review confirms that user needs that fall under Usable and even Pleasurable are being expressed, but the quality standards for these are either providing design principles or failing to consider them at all. This may result from insufficient consideration of users when designing quality standards in terms of ergonomics. Therefore, expanding the concept of quality for user-centered design of collaborative robotics technologies could be combined with ergonomic evaluation methodologies such as usability or emotional evaluation. This study provides information on the quality attributes of collaborative robots that are necessary to fulfill user requirements, and it is expected that users' perceptions and experiences with collaborative robots will be improved based on this study. In future research, it is necessary to utilize a user-centered approach to develop quality evaluation systems and standards that reflect dynamic user needs in the field of collaborative robot technology, where user experience has not been accumulated. For this purpose, we plan to conduct follow-up research to develop a method for evaluating the satisfaction of user needs and a rating standard according to the level of satisfaction.

AUTHOR CONTRIBUTIONS

In Seok Heo: Conceptualization; methodology; validation; formal analysis; investigation; resources collection; data curation; writing-original draft preparation; writing-review and editing; visualization. **Alivia K. H. Putri**: Formal analysis; investigation; resources collection; data curation; writing-original draft preparation; writing-review and editing; visualization. **Beom Su Kim**: Formal analysis; investigation; resources collection; data curation; visualization. **Min Seong Kwon**: Formal analysis; investigation; resources collection; data curation; visualization. **Sang Ho Kim**: Conceptualization; methodology; validation; writing-review and editing; supervision.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No.2021R1A2C2095410).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study. The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

ORCID

In Seok Heo http://orcid.org/0000-0002-6224-2027
Sang Ho Kim https://orcid.org/0000-0003-0599-289X

REFERENCES

Aaltonen, I., & Salmi, T. (2019). Experiences and expectations of collaborative robots in industry and academia: Barriers and development needs. *Procedia Manufacturing*, *38*, 1151–1158. https://doi.org/10.1016/j.promfg.2020.01.204

Aaltonen, I., Salmi, T., & Marstio, I. (2018). Refining levels of collaboration to support the design and evaluation of human-robot interaction in the manufacturing industry. *Procedia CIRP*, *72*, 93–98. https://doi.org/10.1016/j.procir.2018.03.214

Adamides, G., Christou, G., Katsanos, C., Xenos, M., & Hadzilacos, T. (2014). Usability guidelines for the design of robot teleoperation: A taxonomy. *IEEE Transactions on Human-Machine Systems*, *45*(2), 256–262. https://doi.org/10.1109/THMS.2014.2371048

Ajaykumar, G., & Huang, C. M. (2020). User needs and design opportunities in end-user robot programming. *Companion of the 2020 ACM/IEEE International Conference on Human-Robot Interaction*, 93–95. https://doi.org/10.1145/3371382.3378300

Arents, J., Abolins, V., Judvaitis, J., Vismanis, O., Oraby, A., & Ozols, K. (2021). Human–robot collaboration trends and safety aspects: A systematic review. *Journal of Sensor and Actuator Networks*, *10*(3), 48. https://doi.org/10.3390/jsan10030048

Arents, J., & Greitans, M. (2022). Smart industrial robot control trends, challenges and opportunities within manufacturing. *Applied Sciences*, *12*(2), 937. https://doi.org/10.3390/app12020937

Banjanin, M. K., Stojčić, M., Danilović, D., Ćurguz, Z., Vasiljević, M., & Puzić, G. (2022). Classification and prediction of sustainable quality of experience of telecommunication service users using machine learning models. *Sustainability*, *14*(24), 17053. https://doi.org/10.3390/su142417053

Baraković, S., Baraković, J., & Bajrić, H. (2010). QoE dimensions and QoE measurement of NGN services. *Proceedings of the 18th Telecommunications Forum, TELFOR 2010*.

Bauer, W., Bender, M., Braun, M., Rally, P., & Scholtz, O. (2016). *Lightweight robots in manual assembly–Best to start simply*. Frauenhofer-Institut für Arbeitswirtschaft und Organisation. https://www.edig.nu/assets/images/content/Studie-Leichtbauroboter-Fraunhofer-IAO-2016-EN.pdf

Belingardi, G., Heydaryan, S., & Chiabert, P. (2017). Application of speed and separation monitoring method in human-robot collaboration: Industrial case study. In *17th International Scientific Conference on Industrial Systems*.

Bethel, C. L., Salomon, K., Murphy, R. R., & Burke, J. L. (2007). Survey of psychophysiology measurements applied to human-robot interaction, *RO-MAN 2007-The 16th IEEE International Symposium on Robot and Human Interactive Communication* (pp. 732–737). IEEE. https://doi.org/10.1109/ROMAN.2007.4415182

Borboni, A., Reddy, K. V. V., Elamvazuthi, I., AL-Quraishi, M. S., Natarajan, E., & Azhar Ali, S. S. (2023). The expanding role of artificial intelligence in collaborative robots for industrial applications: A systematic review of recent works. *Machines*, *11*(1), 111. https://doi.org/10.3390/machines11010111

Box, J. M. F. (1983). Product quality assessment by consumers—The role of product information. *Industrial Management & Data Systems*, *83*(3/4), 25–31. https://doi.org/10.1108/eb057308

Brivio, C., Musolino, V., Alet, P. J., Merlo, M., Hutter, A., & Ballif, C. (2017). Analysis of lithium-ion cells performance, through novel test protocol for stationary applications, *2017 6th International Conference on Clean Electrical Power (ICCEP)* (pp. 410–415). IEEE. https://doi.org/10.1109/ICCEP.2017.8004848

Chacón, A., Ponsa, P., & Angulo, C. (2021). Usability study through a human-robot collaborative workspace experience. *Designs*, *5*(2), 35. https://doi.org/10.3390/designs5020035

Chemweno, P., Pintelon, L., & Decre, W. (2020). Orienting safety assurance with outcomes of hazard analysis and risk assessment: A review of the ISO 15066 standard for collaborative robot systems. *Safety Science*, *129*, 104832. https://doi.org/10.1016/j.ssci.2020.104832

Chowdhury, A., Ahtinen, A., Pieters, R., & Vaananen, K. (2020). User experience goals for designing industrial human-cobot collaboration: A case study of franka panda robot. *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society* (1–13). https://doi.org/10.1145/3419249.3420161

CoLLaboratE Project. (2020). *End-user requirements, use cases and industrial scenarios (preliminary)*. https://collaborate-project.eu/uploads/deliverables/D2.1%20-%20End-user%20requirements,%20use%20cases%20and%20industrial%20scenarios%20(preliminary).pdf

Crespi, N., Molina, B., & Palau, C. E. (2011). QoE aware service delivery in distributed environment, *2011 IEEE Workshops of International Conference on Advanced Information Networking and Applications* (pp. 837–842). IEEE. https://doi.org/10.1109/WAINA.2011.58

Dallel, M., Havard, V., Dupuis, Y., & Baudry, D. (2023). Digital twin of an industrial workstation: A novel method of an auto-labeled data generator using virtual reality for human action recognition in the context of human–robot collaboration. *Engineering Applications of Artificial Intelligence*, *118*, 105655. https://doi.org/10.1016/j.engappai.2022.105655

Dmytriyev, Y., Zaki, A. M. A., Carnevale, M., Insero, F., & Giberti, H. (2021). Brain computer interface for human-cobot interaction in industrial applications, *2021 3rd International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA)* (pp. 1–6). IEEE. https://doi.org/10.1109/HORA52670.2021.9461383

Elprama, S. A., Jewell, C. I., Jacobs, A., El Makrini, I., & Vanderborght, B. (2017). Attitudes of factory workers towards industrial and collaborative robots. *Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction* (113–114). https://doi.org/10.1145/3029798.3038309

Faccio, M., Minto, R., Rosati, G., & Bottin, M. (2020). The influence of the product characteristics on human-robot collaboration: A model for the performance of collaborative robotic assembly. *The International Journal of Advanced Manufacturing Technology*, *106*, 2317–2331. https://doi.org/10.1007/s00170-019-04670-6

Francesco, P., & Paolo, G. G. (2017). AURA: An example of collaborative robot for automotive and general industry applications. *Procedia Manufacturing*, *11*, 338–345. https://doi.org/10.1016/j.promfg.2017.07.116

Franklin, C. S., Dominguez, E. G., Fryman, J. D., & Lewandowski, M. L. (2020). Collaborative robotics: New era of human–robot cooperation in the workplace. *Journal of Safety Research*, *74*, 153–160. https://doi.org/10.1016/j.jsr.2020.06.013

Gasparetto, A., & Scalera, L. (2019). A brief history of industrial robotics in the 20th century. *Advances in Historical Studies*, *08*(1), 24–35. https://doi.org/10.4236/ahs.2019.81002

Gleirscher, M., Johnson, N., Karachristou, P., Calinescu, R., Law, J., & Clark, J. (2022). Challenges in the safety-security co-assurance of collaborative industrial robots. *The 21st Century Industrial Robot: When Tools Become Collaborators* (191–214). https://doi.org/10.48550/arXiv.2007.11099

Gualtieri, L., Palomba, I., Merati, F. A., Rauch, E., & Vidoni, R. (2020). Design of human-centered collaborative assembly workstations for the improvement of operators' physical ergonomics and production efficiency: A case study. *Sustainability*, *12*(9), 3606. https://doi.org/10.3390/su12093606

Gualtieri, L., Rauch, E., Rojas, R., Vidoni, R., & Matt, D. T. (2018). Application of axiomatic design for the design of a safe collaborative human-robot assembly workplace, *MATEC Web of Conferences* (223, p. 01003). EDP Sciences. https://doi.org/10.1051/matecconf/201822301003

Hägele, M., Nilsson, K., Pires, J. N., & Bischoff, R. (2016). Industrial robotics. In O. Khatib & B. Siciliano (Eds.), *Springer handbook of robotics* (pp. 1385–1422). Springer International Publishing.

Hietanen, A., Pieters, R., Lanz, M., Latokartano, J., & Kämäräinen, J. K. (2020). AR-based interaction for human-robot collaborative manufacturing. *Robotics and Computer-Integrated Manufacturing*, *63*, 101891. https://doi.org/10.1016/j.rcim.2019.101891

Huang, Q., Liu, P., Zeng, H., & Zheng, R. (2022). Research of evaluation method of cleaning performance for cleaning robots based on machine learning, *2022 12th International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER)* (pp. 1275–1280). IEEE. https://doi.org/10.1109/CYBER55403.2022.9907387

Hvilshøj, M., Bøgh, S., Skov Nielsen, O., & Madsen, O. (2012). Autonomous industrial mobile manipulation (AIMM): Past, present and future. *Industrial Robot: An International Journal*, *39*(2), 120–135. https://doi.org/10.1108/01439911211201582

International Electrotechnical Commission. (2016). *IEC 62849:2016 performance evaluation methods of mobile household robots*.

International Electrotechnical Commission. (2018). *IEC 62660-1:2018 secondary lithium-ion cells for the propulsion of electric road vehicles—Part 1: Performance testing*.

International Organization for Standardization. (1998). *ISO 9283:1998 manipulating industrial robots—Performance criteria and related test methods*.

International Organization for Standardization. (2010). *ISO 13855:2010. Safety of machinery—Positioning of safeguards with respect to the approach speeds of parts of the human body*.

International Organization for Standardization. (2011). *ISO 10218-1:2011 robots and robotic devices—Safety requirements for industrial robots—Part 1: Robots*.

International Organization for Standardization. (2012). *ISO 13849-2:2012 safety of machinery—Safety-related parts of control systems—Part 2: Validation*.

International Organization for Standardization. (2013). *ISO/TS 20282-2:2013 usability of consumer products and products for public use—Part 2: Summative test method*.

International Organization for Standardization. (2014). *ISO 13482:2014 robots and robotic devices—Safety requirements for personal care robots*.

International Organization for Standardization. (2015). *ISO 13849-1:2015 safety of machinery—Safety-related parts of control systems—Part 1: General principles for design*.

International Organization for Standardization. (2016). *ISO/TS 15066:2016 Robots and robotic devices–Collaborative robots*.

International Organization for Standardization. (2020). *ISO/TR 23482-1:2020 Robotics—Application of ISO 13482—Part 1: Safety-related test methods*.

International Organization for Standardization. (2021). *ISO 22166-1:2021 robotics—Modularity for service robots—Part 1: General requirements*.

Kadir, B. A., Broberg, O., & Souza da Conceição, C. (2018). Designing human-robot collaborations in industry 4.0: Explorative case studies. *In DS 92: Proceedings of the DESIGN 2018 15th International Design Conference*, 601–610. https://doi.org/10.21278/idc.2018.0319

Kaiser, L., Schlotzhauer, A., & Brandstötter, M. (2018). Safety-related risks and opportunities of key design-aspects for industrial human-robot collaboration, In *Interactive Collaborative Robotics: Third International Conference, ICR 2018, Leipzig, Germany, September 18–22, 2018, Proceedings* (pp. 95–104). Springer International Publishing. https://doi.org/10.1007/978-3-319-99582-3_11

Karagiannis, P., Kousi, N., Michalos, G., Dimoulas, K., Mparis, K., Dimosthenopoulos, D., Tokçalar, Ö., Guasch, T., Gerio, G. P., & Makris, S. (2022). Adaptive speed and separation monitoring based on switching of safety zones for effective human robot collaboration. *Robotics and Computer-Integrated Manufacturing*, *77*, 102361. https://doi.org/10.1016/j.rcim.2022.102361

Khamaisi, R. K., Prati, E., Peruzzini, M., Raffaeli, R., & Pellicciari, M. (2021). UX in AR-supported industrial human–robot collaborative tasks: A systematic review. *Applied Sciences*, *11*(21), 10448. https://doi.org/10.3390/app112110448

Kildal, J., Tellaeche, A., Fernández, I., & Maurtua, I. (2018). Potential users' key concerns and expectations for the adoption of cobots. *Procedia CIRP*, *72*, 21–26. https://doi.org/10.1016/j.procir.2018.03.104

Kokotinis, G., Michalos, G., Arkouli, Z., & Makris, S. (2023). On the quantification of human-robot collaboration quality. *International Journal of Computer Integrated Manufacturing*, *36*(10), 1431–1448. https://doi.org/10.1080/0951192X.2023.2189304

Kumar, S., Savur, C., & Sahin, F. (2021). Survey of human–robot collaboration in industrial settings: Awareness, intelligence, and compliance. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *51*(1), 280–297. https://doi.org/10.1109/TSMC.2020.3041231

Kumičáková, D., Tlach, V., & Císar, M. (2016). Testing the performance characteristics of manipulating industrial robots. *Transactions of the VŠB—Technical University of Ostrava, Mechanical Series*, *62*, 39–50. https://doi.org/10.22223/tr.2016-1/2009

Kwon, W. Y., & Suh, I. H. (2014). Planning of proactive behaviors for human–robot cooperative tasks under uncertainty. *Knowledge-Based Systems*, *72*, 81–95. https://doi.org/10.1016/j.knosys.2014.08.021

Lanter, D., & Essinger, R. (2017). User-centered design. In D. Richardson, N. Castree, M. F. Goodchild, A. Kobayashi, W. Liu, & R. A. Marston (Eds.), *The International Encyclopedia of Geography: People, the Earth, Environment, and Technology* (pp. 1–4). Wiley-Blackwell. https://doi.org/10.1002/9781118786352.wbieg0432

Li, L., Rong, M., & Zhang, G. (2015). An Internet of Things QoE evaluation method based on multiple linear regression analysis. *2015 10th International Conference on Computer Science & Education (ICCSE)* (pp. 925–928). IEEE. https://doi.org/10.1109/ICCSE.2015.7250382

Mahmud, R., Srirama, S. N., Ramamohanarao, K., & Buyya, R. (2019). Quality of experience (QoE)-aware placement of applications in Fog computing environments. *Journal of Parallel and Distributed Computing*, *132*, 190–203.

Malik, A. A., Masood, T., & Bilberg, A. (2020). Virtual reality in manufacturing: Immersive and collaborative artificial-reality in design of human-robot workspace. *International Journal of Computer Integrated Manufacturing*, *33*(1), 22–37. https://doi.org/10.1080/0951192X.2019.1690685

Malm, T., Salmi, T., Marstio, I., & Montonen, J. (2019). Dynamic safety system for collaboration of operators and industrial robots. *Open Engineering*, *9*(1), 61–71. https://doi.org/10.1515/eng-2019-0011

De Marez, L., & De Moor, K. (2007). The challenge of user-and QoE-centric research and product development in today's ICT environment. *Observatorio*, *1*(3), 1–22.

Marvel, J. A., & Norcross, R. (2017). Implementing speed and separation monitoring in collaborative robot workcells. *Robotics and Computer-*

Integrated Manufacturing, 44, 144–155. https://doi.org/10.1016/j.rcim.2016.08.001

Maurtua, I., Ibarguren, A., & Tellaeche, A. (2012). Robotic solutions for footwear industry, *Proceedings of 2012 IEEE 17th International Conference on Emerging Technologies & Factory Automation (ETFA 2012)* (pp. 1–4). IEEE. https://doi.org/10.1109/ETFA.2012.6489780

Medina, A. C., Mora, J. F., Martinez, C., Barrero, N., & Hernandez, W. (2019). Safety protocol for collaborative human-robot recycling tasks. *IFAC-PapersOnLine*, *52*(13), 2008–2013. https://doi.org/10.1016/j.ifacol.2019.11.498

Michalos, G., Kousi, N., Karagiannis, P., Gkournelos, C., Dimoulas, K., Koukas, S., Mparis, K., Papavasileiou, A., & Makris, S. (2018). Seamless human robot collaborative assembly–An automotive case study. *Mechatronics*, *55*, 194–211. https://doi.org/10.1016/j.mechatronics.2018.08.006

Mitra, K., Zaslavsky, A., & Ahlund, C. (2015). Context-aware QoE modelling, measurement, and prediction in mobile computing systems. *IEEE Transactions on Mobile Computing*, *14*(5), 920–936. https://doi.org/10.1109/TMC.2013.155

Murashov, V., Hearl, F., & Howard, J. (2016). Working safely with robot workers: Recommendations for the new workplace. *Journal of Occupational and Environmental Hygiene*, *13*(3), D61–D71. https://doi.org/10.1080/15459624.2015.1116700

Oberer-Treitz, S., Dietz, T., & Verl, A. (2013). Safety in industrial applications: From fixed fences to direct interaction, *IEEE ISR 2013* (pp. 1–4). IEEE. https://doi.org/10.1109/ISR.2013.6695745

Pagani, R., Nuzzi, C., Ghidelli, M., Borboni, A., Lancini, M., & Legnani, G. (2021). Cobot user frame calibration: Evaluation and comparison between positioning repeatability performances achieved by traditional and vision-based methods. *Robotics*, *10*(1), 45. https://doi.org/10.3390/robotics10010045

Panagou, S., Fruggiero, F., & Lambiase, A. (2022). Human gesture system in human robot interaction for reliability analysis. *Procedia Computer Science*, *200*, 1788–1795. https://doi.org/10.1016/j.procs.2022.01.379

Papavasileiou, A., Aivaliotis, P., Aivaliotis, S., & Makris, S. (2022). An optical system for identifying and classifying defects of metal parts. *International Journal of Computer Integrated Manufacturing*, *35*(3), 326–340. https://doi.org/10.1080/0951192X.2021.1992660

Pedrocchi, N., Malosio, M., & Tosatti, L. M. (2009). Safe obstacle avoidance for industrial robot working without fences. *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems* (pp. 3435–3440). IEEE. https://doi.org/10.1109/IROS.2009.5353980

Perez-Ubeda, R., Gutierrez, S. C., Zotovic, R., & Lluch-Cerezo, J. (2019). Study of the application of a collaborative robot for machining tasks. *Procedia Manufacturing*, *41*, 867–874. https://doi.org/10.1016/j.promfg.2019.10.009

Pizzagalli, S. L., Kuts, V., & Otto, T. (2021). User-centered design for Human-Robot Collaboration systems, *IOP Conference Series: Materials Science and Engineering* (1140, p. 012011). IOP Publishing. No. 1. https://doi.org/10.1088/1757-899X/1140/1/012011

Pollák, M., Kočiško, M., Paulišin, D., & Baron, P. (2020). Measurement of unidirectional pose accuracy and repeatability of the collaborative robot UR5. *Advances in Mechanical Engineering*, *12*(12), 168781402097289. https://doi.org/10.1177/1687814020972893

Prati, E., Peruzzini, M., Pellicciari, M., & Raffaeli, R. (2021). How to include user experience in the design of human-robot interaction. *Robotics and Computer-Integrated Manufacturing*, *68*, 102072. https://doi.org/10.1016/j.rcim.2020.102072

Prati, E., Villani, V., Grandi, F., Peruzzini, M., & Sabattini, L. (2021). Use of interaction design methodologies for human–robot collaboration in industrial scenarios. *IEEE Transactions on Automation Science and Engineering*, *19*(4), 3126–3138. https://doi.org/10.1109/TASE.2021.3107583

Qureshi, M. Z., Azhar, A., Abubakar, Q., Rana, T. A., & Maqbool, A. (2021). Capturing users requirements using a data mining approach, *2021 International Conference on Communication Technologies (ComTech)* (pp. 49–54). IEEE. https://doi.org/10.1109/ComTech52583.2021.9616939

Rehman Laghari, K. U., & Connelly, K. (2012). Toward total quality of experience: A QoE model in a communication ecosystem. *IEEE Communications Magazine*, *50*(4), 58–65. https://doi.org/10.1109/MCOM.2012.6178834

Safeea, M., & Neto, P. (2022). Precise positioning of collaborative robotic manipulators using hand-guiding. *The International Journal of Advanced Manufacturing Technology*, *120*(7–8), 5497–5508. https://doi.org/10.1007/s00170-022-09107-1

Sandini, G., Mohan, V., Sciutti, A., & Morasso, P. (2018). Social cognition for human-robot symbiosis—Challenges and building blocks. *Frontiers in Neurorobotics*, *12*, 34. https://doi.org/10.3389/fnbot.2018.00034

Sawai, K., Nomaguchi, Y., & Fujita, K. (2017). Case study of extended product architecture design for modularization reflecting customer needs of industrial robots. *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, *11*(4), JAMDSM0050. https://doi.org/10.1299/jamdsm.2017jamdsm0050

Schoen, A., Henrichs, C., Strohkirch, M., & Mutlu, B. (2020). Authr: A task authoring environment for human-robot teams. *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, 1194–1208. https://doi.org/10.1145/3379337.3415872

Segura, P., Lobato-Calleros, O., Ramírez-Serrano, A., & Hernández-Martínez, E. G. (2022). Safety assurance in human-robot collaborative systems: A survey in the manufacturing industry. *Procedia CIRP*, *107*, 740–745. https://doi.org/10.1016/j.procir.2022.05.055

Shin, D. H. (2017). Conceptualizing and measuring quality of experience of the Internet of things: Exploring how quality is perceived by users. *Information & Management*, *54*(8), 998–1011. https://doi.org/10.1016/j.im.2017.02.006

Singh, B., Sellappan, N., & Kumaradhas, P. (2013). Evolution of industrial robots and their applications. *International Journal of Emerging Technology and Advanced Engineering*, *3*(5), 763–768.

Slamani, M., Joubair, A., & Bonev, I. A. (2015). A comparative evaluation of three industrial robots using three reference measuring techniques. *Industrial Robot: An International Journal*, *42*(6), 572–585. https://doi.org/10.1108/IR-05-2015-0088

Slamani, M., Nubiola, A., & Bonev, I. (2012). Assessment of the positioning performance of an industrial robot. *Industrial Robot: An International Journal*, *39*(1), 57–68. https://doi.org/10.1108/01439911211192501

Soni, A., Saxena, A., & Bajaj, P. (2020). A methodological approach for mining the user requirements using apriori algorithm. *Journal of Cases on Information Technology*, *22*(4), 1–30. https://doi.org/10.4018/JCIT.2020100101

Still, B., & Crane, K. (2017). *Fundamentals of user-centered design: A practical approach*. CRC Press.

Strazdas, D., Hintz, J., Khalifa, A., Abdelrahman, A. A., Hempel, T., & Al-Hamadi, A. (2022). Robot system assistant (RoSA): Towards intuitive multi-modal and multi-device human-robot interaction. *Sensors*, *22*(3), 923. https://doi.org/10.3390/s22030923

Szabo, S., Shackleford, W., Norcross, R., & Marvel, J. (2012). *A testbed for evaluation of speed and separation monitoring in a human robot collaborative environment*. US Department of Commerce, National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/ir/2012/NIST.IR.7851.pdf

Tihay, D., & Perrin, N. (2018). Human-robot co-activity: needs analysis. *Proceedings of the 9th International Conference on Safety of Industrial Automated Systems SIAS*, 40–47.

Tsarouchi, P., Matthaiakis, A. S., Makris, S., & Chryssolouris, G. (2017). On a human-robot collaboration in an assembly cell. *International Journal* *of Computer Integrated Manufacturing*, *30*(6), 580–589. https://doi.org/10.1080/0951192X.2016.1187297

Tzavara, E., Angelakis, P., Veloudis, G., Gkournelos, C., & Makris, S. (2021). Worker in the loop: A framework for enabling human-robot collaborative assembly, Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems: IFIP WG 5.7 International Conference, APMS 2021, Nantes, France, September 5–9, 2021, *Proceedings*, *Part I* (pp. 275–283). Springer International Publishing. https://doi.org/10.1007/978-3-030-85874-2_29

Valori, M., Scibilia, A., Fassi, I., Saenz, J., Behrens, R., Herbster, S., Bidard, C., Lucet, E., Magisson, A., Schaake, L., Bessler, J., Prange-Lasonder, G. B., Kühnrich, M., Lassen, A. B., & Nielsen, K. (2021). Validating safety in human–robot collaboration: Standards and new perspectives. *Robotics*, *10*(2), 65. https://doi.org/10.3390/robotics10020065

Vicentini, F. (2020). Terminology in safety of collaborative robotics. *Robotics and Computer-Integrated Manufacturing*, *63*, 101921. https://doi.org/10.1016/j.rcim.2019.101921

Vicentini, F. (2021). Collaborative robotics: A survey. *Journal of Mechanical Design*, *143*(4), 1–20. https://doi.org/10.1115/1.4046238

Wang, L., Gao, R., Váncza, J., Krüger, J., Wang, X. V., Makris, S., & Chryssolouris, G. (2019). Symbiotic human-robot collaborative assembly. *CIRP Annals*, *68*(2), 701–726. https://doi.org/10.1016/j.cirp.2019.05.002

Wang, Y., & Yu, S. (2016). Design for dynamic requirement and diverse user experience. *DS 84: Proceedings of the DESIGN 2016 14th International Design Conference* (pp. 553–560).

Weiss, A., Wortmeier, A. K., & Kubicek, B. (2021). Cobots in industry 4.0: A roadmap for future practice studies on human–robot collaboration. *IEEE Transactions on Human-Machine Systems*, *51*(4), 335–345. https://doi.org/10.1109/THMS.2021.3092684

Zhou, Y., Wang, F., Xin, T., Wang, X., Liu, Y., & Cong, L. (2022). Discussion on international standards related to testing and evaluation of lithium battery energy storage. *Distributed Generation & Alternative Energy Journal*, *37*(3), 435–448. https://doi.org/10.13052/dgaej2156-3306.3732

Zöller, S. (2019). *Mapping individual subjective values to product design: An attitudes-based approach for user centered design*. FAU University Press.

Zou, Y., Kim, D., Norman, P., Espinosa, J., Wang, J. C., & Virk, G. S. (2022). Towards robot modularity—A review of international modularity standardization for service robots. *Robotics and Autonomous Systems*, *148*, 103943. https://doi.org/10.1016/j.robot.2021.103943

How to cite this article: Heo, I. S., Putri, A. K. H., Kim, B. S., Kwon, M. S., & Kim, S. H. (2023). Analysis of Quality Standards for Industrial Collaborative Robots based on User-centered Design Framework. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 1–18. https://doi.org/10.1002/hfm.21014