International Journal of Robotics and Automation, Vol. 39, No. 10, 2024
An Open Access Paper

CONSISTENCY ANALYSIS AND SUGGESTIONS OF COLLISION MEASUREMENT IN HUMAN–ROBOT COLLABORATION SAFETY EVALUATION

Xiaopeng Zhu*,** Ke Zhang,** and Xueming Hua**

Abstract

Collaborative robot has the advantages of human–robot collaboration (HRC), being cost-effective and flexible to deploy, and having wide application prospect. Operators may have expected or unexpected contact with the robot during collaboration, which brings potential risks caused by collision. Due to the complexity of collision measurement and the absence of sophisticated standards, huge controversy on what a collaborative robot is safe occurs. We first point out that there are two long-standing issues in collision measurements that cannot be completely solved in a short time. Motivated by the pressing safety needs of a fast-growing collaborative robot industry, it is now increasingly urgent to ensure consistency of collision measurements to avoid controversy. Based on the current achievements, an overall methodology for collision testing is summarised and key technical issues are identified. Influencing factors of human–robot collision measurement are first analysed systematically and discussed thoroughly. Corresponding suggestions are proposed to ensure the result consistency of collision measurement, having great practical value and broad promotion potentiality. This fills the gap between the insufficient safety standards and the urgent need of collaborative robot safety evaluation. Moreover, suggestions for standards in the future will provide strong support for collaborative robot safety.

Key Words

Human–robot collaboration; collision measurement; safety; result consistency; collaborative robot

* National Robot Test and Evaluation Center (Headquarter), Shanghai Electrical Apparatus Research Institute (Group) Co., Ltd., Shanghai, China 200063; e-mail: zhuxiaopeng152457@163.com
** Shanghai Key Laboratory of Laser Manufacturing & Material Modification, Shanghai Jiao Tong University, Shanghai, China 200240; e-mail: {zhangke, xmhua}@sjtu.edu.cn
Corresponding author: Xiaopeng Zhu

Recommended by Zhuming Bi
(DOI: 10.2316/J.2024.206-1058)

1. Introduction

Human–robot collaboration (HRC) will become the intrinsic characteristic of the next generation of robots, which can effectively combine the repetitive performance of robots with the skills and abilities of people, leading to a revolution in the role of robots in manufacturing processes [1]–[4], HRC safety is the foundation of the product design [5], [6]. However, a barrier to the widespread adoption of these collaborative robots is how to certify their safety when working with humans [7].

To achieve safety, robotic applications traditionally exclude operators' access to the scope of robot workspace while the robot is active. Instead, collaborative robot removes the fences, and people can share the common workspace with robots to fulfill a specific task. Thus, various kinds of contact will occur between the robot and the body parts of the operator. Reference [8] given a classification of undesired contact scenarios that could potentially lead to human injury: unconstrained impact, secondary impact, clamping in robot structure, partially constrained impact, and constrained impact. To analyse various aspects of the most significant injury mechanisms, [9] contrasted the traditional industrial robots with collaborative robots in terms of autonomy, collaboration, and task, and listed examples of induced hazards. Reference [10] pointed out that traditional robotic cells have common risk features as the robotic cell is isolated, so mechanical risk management is more homogeneous and standardised. However, in the case of collaborative robots, the situation will be heterogeneous, complex.

A lot of research and practical works on collision safety measurement have been carried out to validate the proposed method of HRC safety or conduct further research about its unclear issues, which can be divided into two categories as the followings:

1) *Pressure/force measurement device (PFMD) design and improvement, which is to substitute the impacting body sites to simulate human–robot collision and measure*

pressures/forces at the same time. Commercial portable collision measurement devices, such as Cobosafe [11] and Pilz robot measurement system (PRMS) [12] are applied to evaluate if the robot is safe enough to realise collaboration. Reference [13] have developed a manually adjusting measurement system meeting the test requirements of different collaborative robot positions and postures, utilising distributed pressure sensor, and force sensor. Reference [14] designed a stationary type safety detection system, compact RIO was used as the controller,the force sensor and laser displacement sensor were used for data collection, and a calibration method based on standard weights impacting was also proposed. Reference [15] modified the Kapuskasing Style Drop Impact Tester to meet the needs of dynamic impact testing and calibration, in which a spring-supported test specimen plate was used to simulate the stiffness of various parts of the human body underneath the skin and surface soft muscle tissue. However, the existing PFMDs are not unified and developed based on their understanding of the measurement of human–robot collision, and have many operational problems. Reference [16] compared the three installation types of PFMD in transient contact safety measurement, fixed device, linear moveable device, and device on a pendulum, and found that different installation methods will affect the measurement results. The National Institute of Standards and Technology (NIST) developed power and force limiting (PFL) measurement device based on the proposed injury criteria and associated testing guidance provided in the Business & Governmental Insurance Agency (BGIA) report, and found that many manufacturing details of critical components in the system should be improved [7].

2) *Biomechanical threshold limits, the reference value to judge whether a contact event is safe.* Establishing the power and force limits during human–robot impact is another research highlight. Reference [17] given the biomechanical threshold of the human body that citing a pressure pain threshold, bringing about wide arguments in the safety field of collaborative robots. Reference [18] found that pressure distributions on hard tissue (bone) were more heterogeneous and showed more significant peaks benefit the probe when reaching the pressure pain threshold, soft tissue (*e.g.* muscle) created a distinct distribution with higher pressure, especially around the corners of the probe. Reference [18] also suggested that peak pressures could be relevant for pain onset and should be accounted for in mechanical pain studies. In addition, men as well as manual labourers had relatively high adjusted pressure pain thresholds. Reference [19] assessed pressure pain thresholds for collisions between humans and robots under the assumption that the pain threshold is lower than the mild injury threshold, and measured in 90 male Korean adults. This study indicated that thresholds differed by age and weight. For example, the thresholds of participants < 30 years of age were lower, by 3∼33%, than those of participants aged > 30.

Although significant achievements have been made from the current studies, perfect PFMD with the same characteristics as human tissue and widely representative biomechanical threshold limits are the two long-standing issues that cannot be settled entirely in a short time because of the diversity of population and the lack of statistical data, for example, there will be children and other groups with weak self-protection ability in some HRC scenarios. Besides, those threshold limits on the collaborative robot system are calculated based on pain sensitivity thresholds. Still, the feeling of pain is related to cultural and racial factors, age, sex, fatigue, psychological make-up and emotional security, distraction and attention, suggestion, attitude, and mood [20], and these factors were not thoroughly considered in those methods currently adopted to collect human body data and calculate the thresholds. Therefore, the two issues require long-standing, in-depth, and systematic work, as well as interdisciplinary knowledge, which needs the cooperation of robotics, medicine, psychology, and other disciplines.

However, driven by the pressing safety needs of a fast-growing collaborative robot industry, the requirements of standardisation and unity of the human–robot collision measurement are now more urgent to ensure the consistency of the test results than that of establishing absolute perfect PFMD and power/force limits.

In this paper, the human–robot collision safety assessment methodology is described in Section 2, which describes the critical procedures of collision measurement and evaluation. The influencing factors of the pressures and forces are systematically analysed in Section 3, categorised as risk assessment, collaborative robot configuration, PFMD design and installation, the basis of evaluation. The consistency of collision measurement is also explicitly described. Section 4 gives corresponding suggestions about collision measurement, including establishing the checklist of significant hazards for collaborative robot, PFMD design optimisation and its calibration, improving the flexibility of PFMD installation in quasi-static contact measurement, *etc.* Conclusions are summarised in Section 5.

2. Human–Robot Collision Safety Assessment Methodology

To focus on the main procedures, the collision safety assessment procedure for collaborative robot is summarised from [21], [22], shown in Fig. 1. As to transient contact, the calculation method is chosen instead of PFMD measurement to acquire the collision force because of reasons mentioned in Section 3.3.2, and Step 3 b) illustrated the difference.

Step 1: Human–robot contact identification. Potential intended or reasonably foreseeable unintended contact situations between an operator and the robot system can be identified by risk assessment, operator body contacting areas, collaborative robot contacting parts, and contact types are the most critical inputs for the following-up procedures.

Step 2: Determine collaborative robot testing points. In the HRC workspace, a collision may occur with the

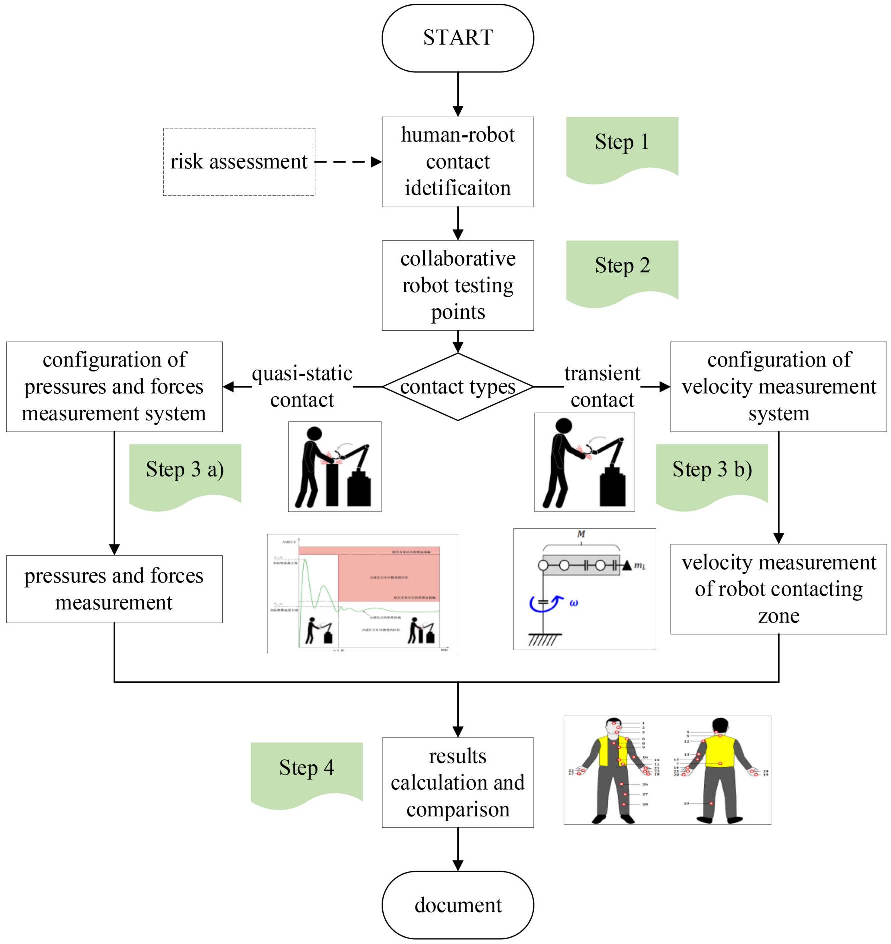

Figure 1. Collision safety assessment procedure.

collaborative robot in different poses, which should be identified before the collision measurement. Meanwhile, other configurations of collaborative robot should be set in the worst case or according to manufacturer's declarations.

Step 3: According to the contact types, the corresponding measurement system is built and configured:

a) For quasi-static contact, a PFMD measurement system is built. PFMD has different modules simulating different human body tissues, which should be installed correctly and adjusted in the measurement sequence. In each test run, a collaborative robot testing pose from Step 2 should be configured.

b) For transient contact, a velocity measurement system is built, which should have the ability to measure the velocity of robot contacting zones. In each test run, a collaborative robot testing pose from Step 2 should be configured.

Step 4: The test results should be calculated correctly and compared with the threshold limits of the human biomechanical model to determine whether it meets the safety requirements.

3. Factors Contributing to Human–robot Collision Measurement

To analyse the influencing factors, we should first define the measure object. Aspects of human–robot collisions include the impacting person and robot [23]. As shown in Fig. 2, to the impacting person, a) body sites, associated with skin tolerance, muscle & fat tolerance, and bone tolerance, b) body attributes (mass, elasticity, *etc.*), c) body dynamics (movement, response, *etc.*). To the collaborative robot, a) static characteristics, including original shape and its deformation, b) robot dynamics, including velocities, accel/decel, elasticity, impact time, and shear force, c) robot behaviour, such as detection or avoidance. As there are workpieces, fixtures, and other installations in the collaboration system, the contact types (quasi-static contact or transient contact) should be considered. PFMDs are substituted for the impacting body sites to simulate the contact events and measure collision pressures/forces simultaneously in Section 2 Step 3 a).

To analyse the factors that contribute to the consistency of human–robot collision measurement, aspects of human–robot collision and the technical parts of ISO/IEC 17025 [24] (management parts are excluded) are taken into account synthetically. ISO/IEC 17025 is a document developed with the objective to promote confidence in laboratory operation, which can guide the analysing process. Factors determining the correctness and reliability of the tests include human factors, accommodation and environmental conditions, test methods and method validation, equipment, measurement traceability, sampling, the handling of test, and calibration items.

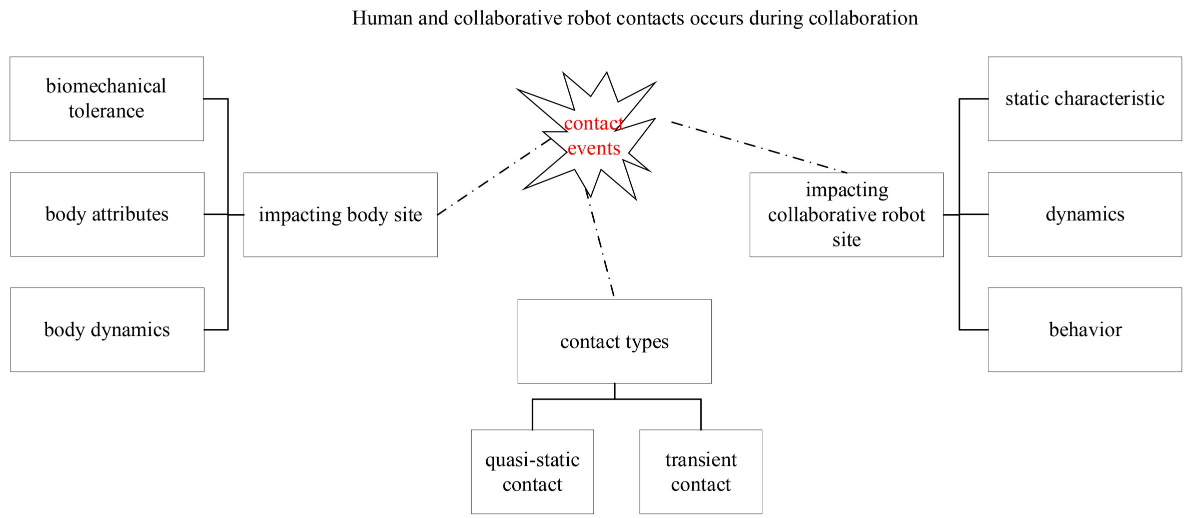

Figure 2. Aspects of human–robot collisions.

The influencing factors of HRC collision measurement can be divided into four categories: a) hazard identification, b) collaborative robot configuration, c) test equipment design and installation, d) results evaluation basis. The influence of these factors and their reasons are discussed in Sections 3.1–3.4.

3.1 Influence of Risk Assessment

The concluded contacted body areas, contacting robot zone, and contact types are the premise of human–robot collision measurement, which determine the sequence of measurements to perform. References [17] and [22] described that the measurement points can be acquired from the risk assessment [25], a widely adopted evaluation method for safety of machinery. The risk assessment procedure is shown in Fig. 3, hazard identification is the most essential step in risk assessment. From its results, a list of hazardous zones, hazards, hazardous situations, and/or hazardous events will be identified, and a collision test case can be generated.

Hazard identification is generally performed by a team of appropriate person(s) [25], [26]. Members have knowledge of different disciplines and various experience and expertise. So human factors, such as experience, skill, and expertise background play an essential role in ensuring the discipline of the process. Different team groups may generate different risk assessment results, especially for those scenarios where hazards are poorly understood. While risk assessment approaches have been widely applied in traditional industries, ensuring uniformity for HRC systems can be challenging for several reasons: 1) design factors of HRC are of high complexity, 2) lack of experience and expert knowledge concerning HRC, 3) human behaviour and error [27]. The collision measurement points – contact body areas, contact robot zone, and contact types, which are the preconditions for HRC collision measurement, will vary with the outcome of hazard identification and affect the consistency of test results.

3.2 Influence of Collaborative Robot Configuration

The principle of collision detection is mainly based on the robot dynamic model [8], [28], [29], which compares the command torque (or the driving current of the motor) with the model-based command (the expected torque in the absence of collision) to confirm the situation of rapid transients due to possible collision [30]. The dynamics of collaborative robot can be illustrated as (1), which describes the joint torque needed to reach a particular state of the manipulator (posture, velocity, and acceleration) [31], [32]:

$$Q = M\left(q\right)\ddot{q} + C\left(q,\dot{q}\right)\dot{q} + F\left(\dot{q}\right) + G\left(q\right) + J\left(q\right)^{T} f \quad (1)$$

Where $q, \dot{q}, \ddot{q}$ are, respectively, the vector of generalised joint coordinates, velocities, and accelerations. M – joint-space inertia matrix, C – Coriolis and centripetal force coupling matrix, F – Friction force, G – Gravity loading, J – Jacobian matrix, f – the joint forces due to a wrench f applied at the end-effector.

M, C, F, G of the robot dynamics model are related to the configuration parameters of the manipulator, such as pose, velocity, acceleration, *etc.* These robot configuration parameters will influence collaborative robot collision detection and reaction, and HRC collision measurements will be affected according to the detection principle.

Similar findings have been reported in measurement of human–robot collision [33]–[35]. Reference [33] conducted experiments on a generic abstraction of a collaborative pick and place task in the laboratory, approved that the exerted force during contact with a human is highly depended on the end effector velocity and the robot configuration, which can partially be explained by the variation of the determinant of the Jacobian matrix for different robot configurations. Reference [34] pointed out that variability occurs in robot velocity, the distance between the robot base and impact location, and the total stiffness of the measurement system. Reference [35] studied the effect of robot pose on peak impact force, considering two different

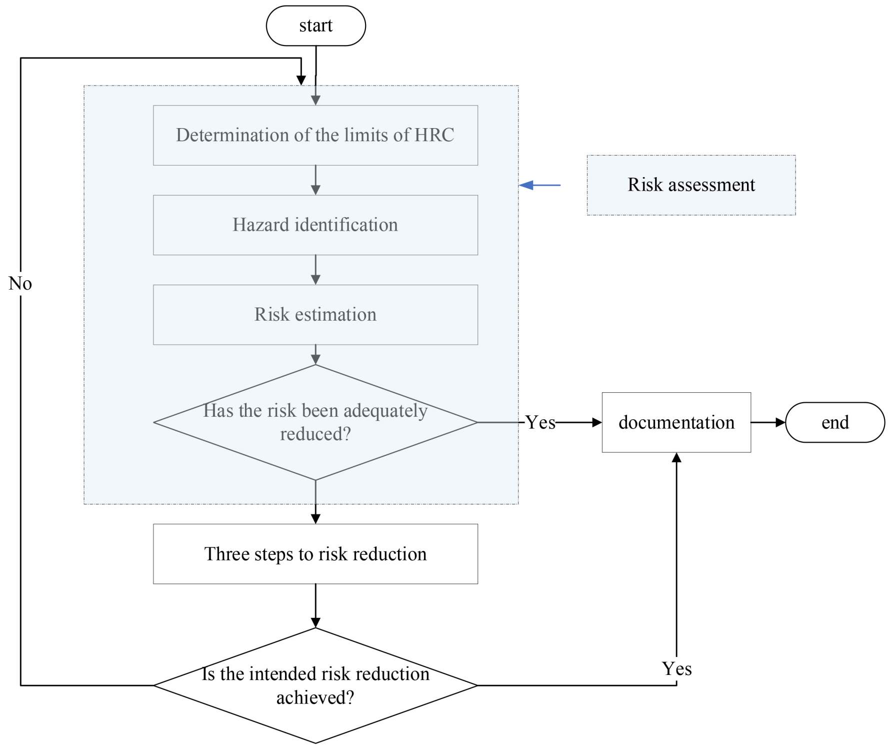

Figure 3. Schematic representation of risk assessment.

positions for the collision, at the centre of the reference cube according to [36] and -5 cm from its outer side, lower peak forces were obtained at the outer edge.

For commercial collaborative robots, other configurable parameters will also affect the test results, such as force perception sensitivity level, and functions of those are to provide convenience to users in various application scenarios.

3.3 Influence of PFMD Design and Its Installation

PFMD has two functions in human–robot collision measurement: one is replicating the related human body tissues to simulate the collision process of between human and collaborative robot, and the other is measuring pressures and forces that operator may suffer from a human–robot collision. A mass-spring damper model has been widely established and is recommended according to the recent final draft international standard (FDIS) version of the [21] and [22]. The spring constant values represent the proportion of soft tissue in body regions. The effective mass value represents a combination of the mass of body region along with the effect of interconnectivity of the body region with adjacent body regions.

3.3.1 PFMD Design

Figure 4 shows a typical design of PFMD from [21], [22]. A base (G) supports a set of linear bearings to allow a plate (E) to move against the resistance of spring (F), and a damping material (C) is placed on the plate (E). Pressure sensing foil (B) and force sensor (G) is used in combination to measure the maximum power and force as well as

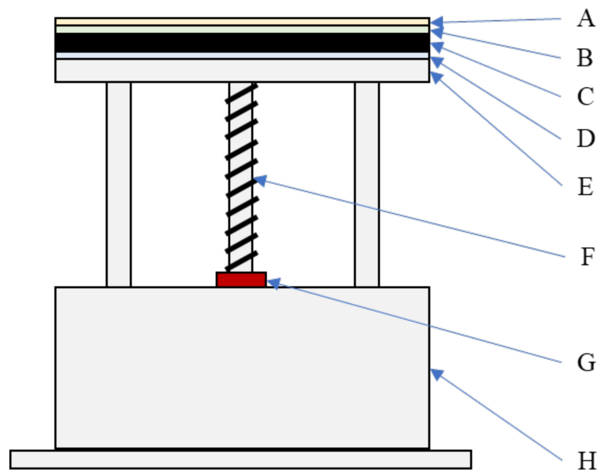

Figure 4. Typical PFMD representation. A – cloth, B – pressure sensing foil, C – damping material, D – teflon film, E – moving plate, F – spring, G – force sensor, H – base.

their temporal traces. Teflon film (D) to minimise friction between the plate (E) and K1 (C) to reduce the effects of shear forces on measurements. Microfibre cloth (A) is used to filter out contact pressure marks that can be created by small contours of the surface at identified contact locations, and its thickness $\leq$0.5 mm. C-damping material and F-spring are used to simulate human biological tissues, whose properties are also specified in standards.

As collision usually occurs in a very short time, pressure/force resolution and range, spatial resolution of pressure sensing, and frequency response, are the critical parameters of PFMD to measure pressures and forces

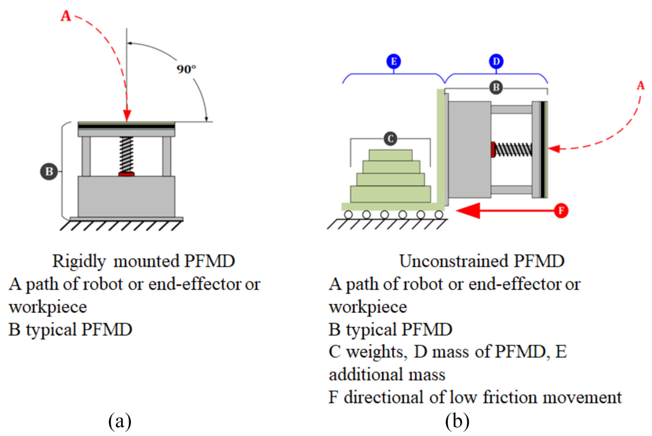

Figure 5. Installation of PFMD.

successfully and accurately, [21], [22] also gives suggestions about these parameters. Still, there are other PFMD design details not illustrated in standards but can influence the collision test result:

1) The connection types between the spring and load cell (G), plate (E). If the spring is not properly connected, it will frequently bounce during the collision measurement, which will have a significant effect on the pressure/force data.
2) The links between the plate (E) and base (H). The links connect the plate (E) and base (H), supporting the load of A∼E, should move freely with the compression of spring. No further information realising this function is provided in current standards.
3) Calibration of PFMD. Damping material shore A hardness values should be verified using ISO 868/ASTM D2240, and springs should be determined as described in ASTM A125-96 or DIN 2096. The full system of PFMD should also be properly calibrated to meet the test requirements for dynamic collisions.

3.3.2 PFMD Installation

During the test, PFMD should be able to simulate the occurrence of human–robot collision, which means PFMD should be able to imitate human behaviour. References [21] and [22] given the installation method of PFMD: for quasi-static contact is shown in Fig. 5(a), the PFMD is to be anchored, stable, and adequately supported on a rigid surface, for transient contact shown in Fig. 5(b), unconstrained PFMD was mounted to a single axis low friction slide and can move freely along the direction of contact as well as replicate the human body region effective mass to directly measure pressure/forces.

There are many operational problems during HRC collision measurement when using the installation methods above:

1) As mentioned in Section 3.2, the collision measurement results are related to robot configuration, pose, and the distance between the measurement points and robot base. Collision measurement is time-consuming, the experimental time for each collision position and robot adjustment requires about 0.87 h [37]. So, the installation of PFMD should be rapidly adapted to suit different robot configurations, which is not described in the existing standards.
2) For transient contact, there is a fatal problem that PFMD can only be installed horizontally, the path of robot or end-effector or workpiece is constrained, which not only brings inconvenience to the experiment but also cause test blind areas in its workspace. So, this methodology has relatively low operability.

3.4 Influence of Evaluation Basis

After the collision measurement data is acquired, human biomechanical threshold limits are the reference value to judge whether a test result is passed. Annex A of [17] provides guidance on how to establish threshold limit values on the collaborative robot system, particularly on PFL applications. A body model, including 29 specific body areas categorised into 12 body regions has been created, and the pressure and force limits based on pain sensitivity [38]–[40] are also shown in Fig. 6.

The following two items needed to be considered when judging the collision measurement results:

1) Threshold limits. If the threshold limits exceed what humans can withstand, the assessment of collaborative safety may be insufficient. If the threshold limits are lower than needed, the cost of collaborative robot will increase, and the usability of collaborative robot will reduce.
2) Movements of operator may occur during collaboration tasks. In HRC, operators are not static and will move around in the collaboration workspace, approaching or leaving away from the robot in operation. It is clear that the risk is higher when the operator is close to the robot than when it is reversed. Also, the human body can be dynamically complex during collisions, the head, hands, legs, and other body parts can move in different manners. This will affect the safety assessment of HRC.

4. Suggestions of Collision Measurement for Collaborative Robot Safety Evaluation

As mentioned in Section 1, perfect PFMD with the same characteristics as human tissue and widely representative biomechanical threshold limits are the two long-standing issues that cannot be settled entirely in a short time. All the same, a certain degree of consensus has been achieved, which was standardized in [17], [22] and will be embodied in [21], especially the PFMD design principle and threshold limits based on the body model. From the analysis and discussion of factors affecting the result consistency in HRC collision measurement, corresponding suggestions were proposed to control the measurement process.

4.1 Establish the Checklist of Significant Hazards for Collaborative Robot

According to the definition of the European Union (EU) Machinery Directive (MD), robot is not a complete machine [41]. Hazards vary with the type of robot used and

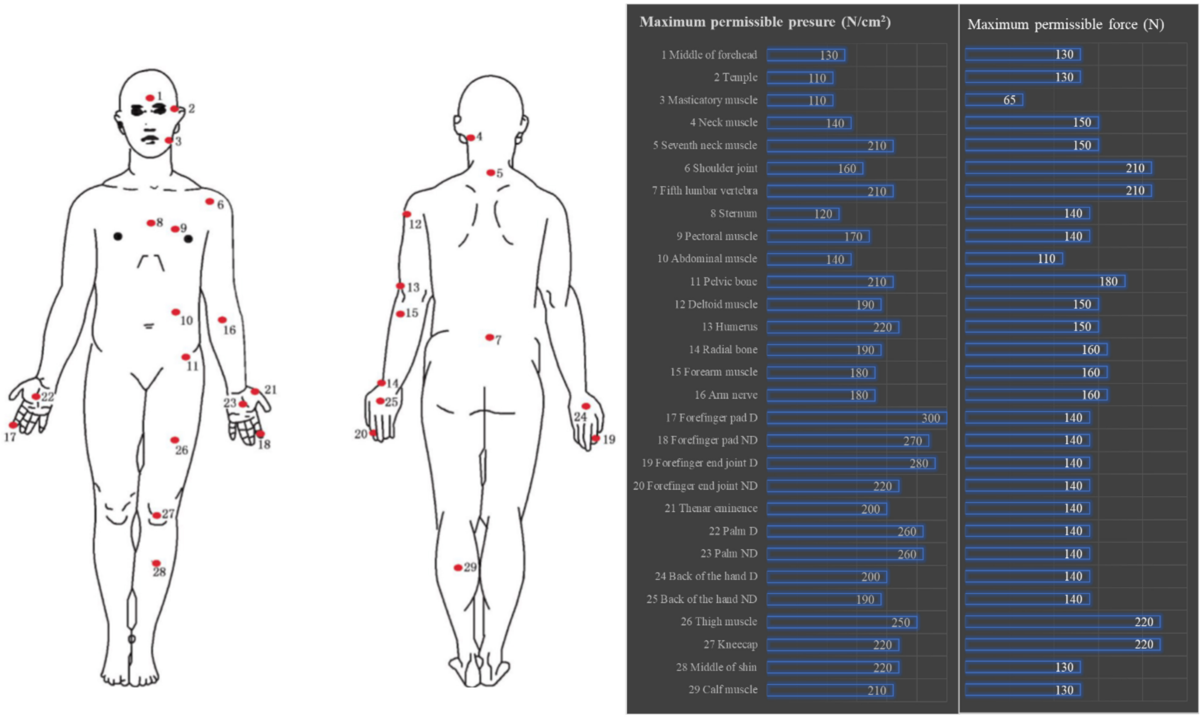

Figure 6. Body model and biomechanical limits in quasi-static contact.

its purpose, and how it is installed, programmed, operated, and maintained. HRC system consists of collaborative robots, end-effectors [42], fixtures, and other components. Meanwhile, human plays an essential role in the HRC system, [43] described a tripartite system in the concept of safety in the future. Although the safety evaluation of HRC should take the whole system into account, and each HRC should be evaluated solely, it is meaningful to conduct collision measurement for the collaborative robot, which is the core of the system. For the company of UNIVERSAL ROBOTS, 80% of the thousands of their collaborative robots worldwide operate without safety guarding (after risk assessment) [44].

Contact events between the collaborative robot and body parts of the operator could come about in a number of ways [17]: a) intended contact situations that are part of the application sequence, b) incidental contact situations, which can be a sequence of not following working procedures but without a technical failure, c) failure modes that lead to contact situations. In addition, unintended behaviour of the operator or reasonably foreseeable misuse should be taken into consideration in determining human–robot contact scenarios, such as loss control of the robot by the operator, behaviour resulting from lack of concentration or carelessness.

For risk identification, numerous methods have been validated in practice or investigated in academic studies. The checklist method [25], failure modes and effects analysis (FEMA), fault tree analysis (FTA), hazard and operability (HAZOP), and other methods have been widely used in engineering. There are also some novel risk assessment approaches. Reference [45] conducted a job safety analysis, where a collaborative assembly is broken down into sub-asks, which are then analysed for hazards. Reference [46] developed SAFER HRC tool using formal verification methods to assess safety in HRC. Reference [27] studied those novel risk assessment approaches in HRC, finding that only few of these novel approaches have found their way into industrial practice.

The checklist method is relatively simple, and practically oriented with respect to those novel methods, so it is widely used in practice. As collaborative robots continue to be used, it has become feasible to create typical human–robot contact scenarios based on the feedback of collaborative robot applications, as hazards of industrial robot shown in [41] Annex A. If the checklist was determined, application experiences, and human factors of risk assessment team members can be solid down, which is quite helpful for the safety evaluation of collaborative robot. Exemplary illustrations are given in Table 1, body region, the contacting robot part, contact type, and typical hazardous situation are suggested to be included in the future standards.

4.2 Select Appropriate Collision Poses in the Workspace of Collaborative Robot

After body regions, robot contact areas, and contact types are identified from risk assessment, the collaborative robot configuration needs to be determined, which means that the robot collides with the operator at what pose, speed, pose acceleration, *etc.* Collision pressures/forces vary with collaborative robot configuration in its workspace described in Section 3.2.

Robot collision poses are the most critical parameter, which is difficult to determine. There are lessons that we can learn from [36], a standard of manipulating industrial robots–performance criteria and related test methods.

Table 1
Exemplary Illustrations of Human–Robot Contact Checklist

No.	Body Region	Robot Part	Contact Type	Typical Hazardous Situation
1	Chest	TCP	Transient contact ■ Quasi-static contact ■	Operator walking around or working in the collaboration workspace, *etc*
2	Hand and finger	Wrist joint 3	Transient contact ■ Quasi-static contact □	Manual loading or unloading in collaboration task, *etc*
...	...	...	Transient contact □ Quasi-static contact □	...

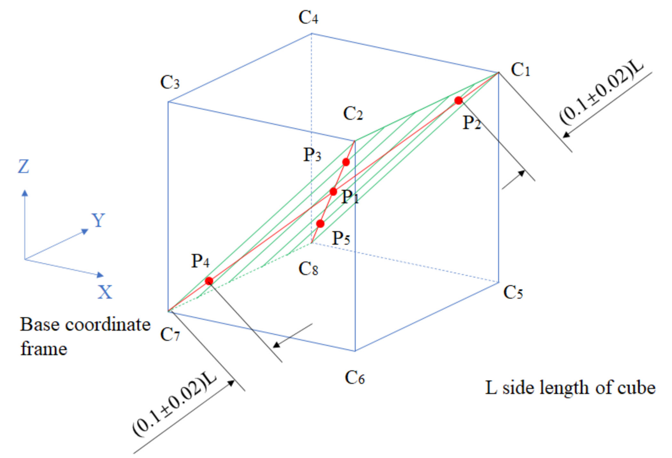

Figure 7. Poses to be used in ISO 9283.

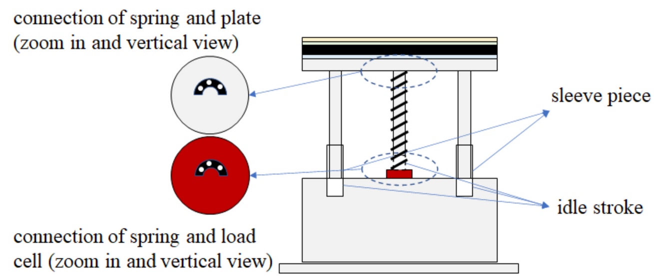

Figure 8. Suggestions of PFMD design.

It gives definitions of poses to be tested and paths to be followed, in which five suitable positions are located in a plane inside a cube within the workspace, shown in Fig. 7. The cube is located in the robot workspace, fulfilling the following requirements: locate in that portion of the workspace with the greatest anticipated use, have the maximum volume allowable with the edges parallel to the base coordinate frame. The robot performance differs with test poses, so five specific points ($P_1 \sim P_5$) are chosen as the testing points to keep its consistency [36].

Although the selection of collision poses is far more complex than performance poses, the principle of the cube determined can be used to select appropriate collision poses in the HRC workspace, and a collision poses reference could be built in future standards. Other configurations can be set as follows: a) speed, and acceleration should be set in the most worth case, b) configurable parameters should be set according to the instruction of the manufacturer, c) the path of collaborative robot should be set, so that the robot contact area is perpendicular to the surface PFMD if at all possible.

4.3 PFMD Design Optimisation and Its Calibration

Suggestions about PFMD design details are shown in Fig. 8 and can be described as following:

1) The upper end-face of the spring should be fixed to the plate (E) by bolts (other fixed types may also be feasible), and the lower end-face fixed to the load cell (G). Spring can deform and absorb contacts during the collision measurement, which plays an essential role to represent the human body regions. If the spring is not well fixed, it will frequently bounce during the collision measurement, having a significant effect on the pressure/forces data.
2) Three or more sleeve pieces should be used to clamp the links between the moving plate (E) and base (H), the friction force and gap between the sleeve piece and the link should be as small as possible. Idle strokes of the link and the spring guide rod should be long enough to make the plate (E) move freely with the spring compression, and plate (E) will move against the resistance of spring in collision test. Sleeve pieces and idle strokes can ensure that the spring is only subjected to the compression force without forces in other directions, especially that the PFMD is not installed horizontally.
3) Dimensions of PFMD components and details of the materials are suggested to be given in the future standards. The weight and stiffness of plate (E) depends on its dimensions and materials, which have effects on the pressure/forces data. The material of cloth (A) used to filter out contact marks is also needed to be determined. Other components have the similar requirements to standardise the PFMD.

The PFMD calculation is suggested to be divided into components calibration and PFMD module calibration. Components, such as damping materials, spring, and load cell, can be calibrated by current standards ISO 868/ASTM D2240, ASTM A125-96/DIN 2096, JJG 860, *etc.* Although no standard for PFMD module calibration currently exists, there are some custom methods developed based on the measurement principle. Reference [14] carried out the calibration with M3 standard weight and the weight falling freely at a fixed height. Reference [15] developed Dynamic Impact Testing and Calibration Instrument (DITCI) to calibrate biosimulant human tissue artefacts. So, PFMD module calibration includes static calibration based on standard weight, which reflects the accuracy of measurement, and dynamic calibration based on standard weight falling freely or in pendulum motion which reflects the dynamic properties of collision.

4.4 Improve the Flexibility of PFMD Installation in Quasi-Static Contact Measurement

During quasi-static contact, the human body is trapped between a moving part of the robot system and another fixed or moving part of the workcell. In such a situation, the robot system would apply pressure or force to the trapped body part for an extended interval until the condition can be alleviated. As mentioned in Section 3.3.2, collision measurement is time-consuming, it is better to improve the flexibility of PFMD installation to avoid a significant expenditure of time and effort. Moreover, to assure the consistency of collision measurement, the experiment conditions should be recorded correctly.

In this paper, a collision safety test system based on an industrial robot application is built, shown in Fig. 9(a). The PFMD module is fixed on the flange plate of an industrial robot (KUKA KR60, as an example). In each test run, KR60 will be programmed to carry the PFMD to the test points. In Fig. 9(b), P2 represents the test point of the collaborative robot, P1, P2, and P3 are the moving path, the red dotted line represents the movement trajectory of the robot contact zone, and at P2, the path of the robot contact zone should be perpendicular to PFMD surface.

The collision safety test system can improve the accessibility of the test area and the convenience of the test process, especially in the case of taking human body-associated data into consideration mentioned in Section 4.6, the industrial robot carrying PFMD can imitate human body movements. It's worth noting that installation and programming of KR60 should be able to ensure that the system has enough rigidity, so that the impact of the installation on the measurement results of the pressures and forces can be negligible.

4.5 Calculate the Collision Force Based on Modified Contact Model for Transient Contact

For transient contact, human parts are impacted by the moving parts of the robot system and can recoil or retract from the robot without being clamped or trapped, thus making for a short duration of the actual contact. In [22], an unconstrained test device composed of PFMD and the human body region effective mass is built, and the PFMD is allowed to move freely along the direction of contact. However, this is not a good choice because of the operational problems mentioned in Section 3.3.2.

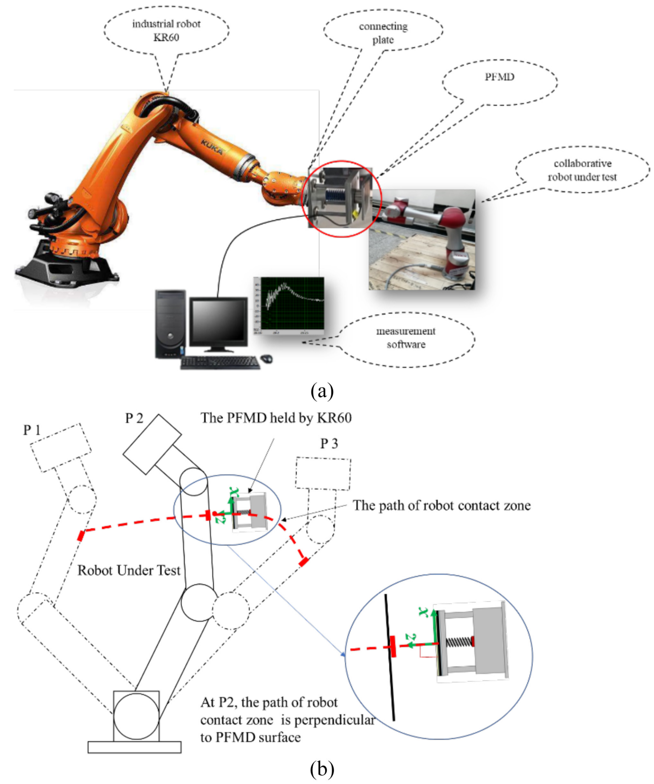

Figure 9. Schematic diagram of collision measurement system.

Alternatively, [17] provides a pressure and force calculation method, modelling the energy transfer limit based on a known body contact region and contact area (ISO/TS contact model). The calculation method is based on the measurement results of the relative speed between the robot and the human body region. So, pressure/force measurement can be replaced by speed measurement instead, which is more convenient to conduct. In this paper, laser tracking technology is suggested to be adopted in transient contact to measure velocity.

4.5.1 ISO/TS Contact Model

To describe this contact scenario, a simply two-body model is used [17], shown in Fig. 10, the effective mass of the robot $\boldsymbol{m_R}$ is moving to come into contact with the effective mass of the human body region $\boldsymbol{m_H}$ at a relative velocity ν_{rel}, across a two-dimensional surface area, resulting in an assumed fully inelastic contact situation, which corresponds to a worst-case assumption. The relative kinetic energy is assumed to be entirely deposited in the affected body region.

The energy in this model is expressed as (2):

$$E = \frac{F^2}{2k} = \frac{1}{2}\mu v_{\text{vel}}^2 \qquad (2)$$

Where:

V_{vel} is the relative speed between the robot and the human body region.

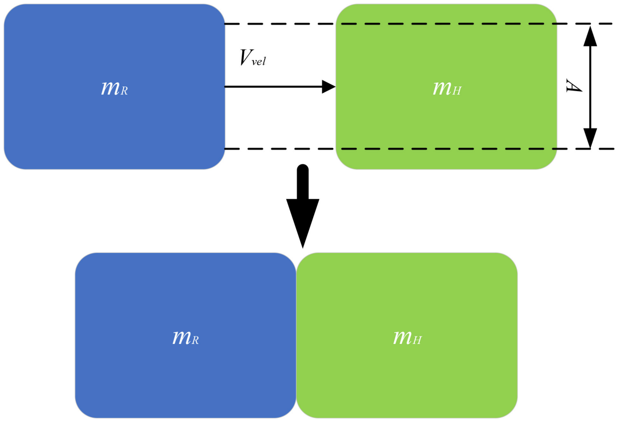

Figure 10. Contact model of transient contact.

μ is the reduced mass of the two-body system, which is expressed by (3):

$$\mu = \left(\frac{1}{m_H} + \frac{1}{m_R}\right)^{-1} \tag{3}$$

m_H is the effective mass of human body region;

m_R is the effective mass of the robot as a function of robot posture and motion in (4):

$$m_R = \frac{M}{2} + m_L \tag{4}$$

m_L is the effective payload of the robot system, including tooling and workpiece;

M is the total mass of the moving parts of the robot.

Thus, solving (2) for v_{vel} gives (5):

$$v_{\text{vel}} = \frac{F}{\sqrt{\mu \text{k}}} \tag{5}$$

This can be directly specified to the maximum permissible force in transient contact $F_{\max}$ in (6), which means the maximum allowable relative speed between shall not exceed $v_{\text{vel,max}}$:

$$v_{\text{vel,max}} = \frac{F_{\max}}{\sqrt{\mu \text{k}}} == \frac{F_{\max}}{\sqrt{k}} \sqrt{\left(\frac{1}{m_H} + \frac{1}{m_R}\right)} \tag{6}$$

4.5.2 Modified Contact Model

Equation (4) is a simplified model to calculate the effective mass in ISO/TS 15066. The simplified model turns out to be not only conservative in most cases, limiting the robot's efficiency and economic use but also may lead to an underestimation of hazards. Reference [47] represented the inertial property in a specific direction of a manipulator using effective mass, given by (7):

$$m_{R,\text{mod}} = \left(u^T J(q) M(q) J(q)^T u\right)^{-1} \tag{7}$$

where $M(q)$ and $J(q)$ are the inertia matrix and the Jacobian matrix of a manipulator, q is the joint angle, and u is the direction vector.

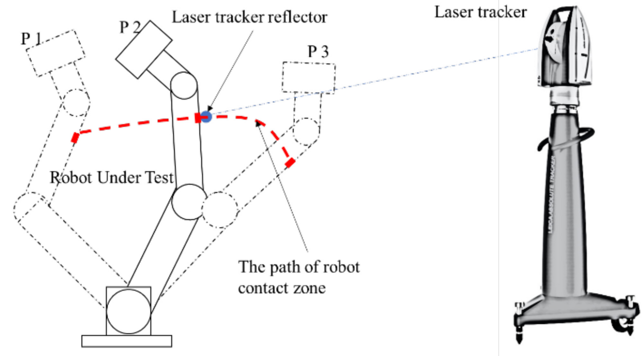

Figure 11. Velocity measurement of robot contacting zone.

Substitute (7) into (6), so $\boldsymbol{v}_{\text{vel,max}}$ is:

$$\begin{aligned} v_{\text{vel,max}} &= \frac{F_{\max}}{\sqrt{\mu \text{k}}} \\ &= \frac{F_{\max}}{\sqrt{k}} \sqrt{\left(\frac{1}{m_H} + u^T J(q) M(q) J(q)^T u\right)} \end{aligned} \tag{8}$$

Reference [48] proposed a method to measure the effective mass using a passive mechanical pendulum setup, and compared the result acquired by the simplified model in (4) provided in [17] and by the dynamic model in (7), finding the error between the experimental results and dynamic model is much less than the simplified ISO/TS model, and the effective mass by ISO/TS model is usually higher than the actual value.

4.5.3 Velocity Measurement of Robot Contacting Zone

The movement speed of different parts of the collaborative robot can be obtained by non-contact measurement. Laser tracking measuring instruments, for example, Leica AT960, have been widely used in industrial measurement fields, which can offer high-speed dynamic measurement having the ability to calculate not just position but orientation [49]. The laser tracker reflector is located at the contacting parts of the collaborative robot, as shown in Fig. 11, the velocity of any robot contact parts can be measured in real-time.

4.6 Take Human Body Associated Data into Consideration

In HRC, operators are not static and will move around in the collaboration workspace, approaching or leaving away from the robot in operation. Also, the human body as a whole can be dynamically complex during collisions, the head, hands, legs, and other body parts can move in different manners. It will affect the safety assessment of HRC.

There are some human kinematics statistical data in the industry, which can be used as an assessment reference. Reference [50] specified parameters based on values for approach speeds of parts of the human body to determine the minimum distances to a hazard zone from the detection zone. The speed of human walking (1600 m/s) and upper limb movement (2000 mm/s) are time-tested and proven in practical experience. Occupational Safety and Health Administration (OSHA) mentions that the speed of the human hand mentioned is 1600 mm/s, giving guidance on safety design for mechanical power presses [51].

Under abnormal working conditions, such as running, jumping, and falling, the speed may be higher or lower than the above values. In the actual measurement work, the above situation can be analysed utilising risk assessment to determine the relevant data [50], [51].

5. Conclusion

In this paper, we firstly pointed out that there are two long-standing issues in human–robot collision measurement that cannot be settled entirely in a short time: a) PFMD with the same characteristics as human biomechanical tissue, b) accurate and widely representative biomechanical threshold of the human body.

Driven by the pressing safety needs of a fast-growing collaborative robot industry, the requirements of standardisation and unity of the human–robot collision measurement are now more urgent to ensure the consistency of the test results than that of establishing perfect PFMD and power/force limits. The influencing factors of human–robot collision measurement are first systematically analysed and thoroughly discussed, which can be categorised into: a) hazard identification, b) collaborative robot configuration, c) test equipment design and installation, d) evaluation basis.

Corresponding suggestions are given to control the consistency of human–robot collision measurement. It is meaningful and has high operability to establish the checklist of significant hazards for collaborative robot. For collaborative robot configuration, the determination of collaborative robot testing points should consider the representative coverage of robot workspace. A series of test points can be determined in the future standard, like the cube in the robot performance test. An industrial robot application solution is proposed to improve the flexibility of PFMD installation in human—robot collision measurement, having the advantage of imitating human body movement. Key design details for optimising PFMD are provided, and calibration methods for key components and PFMD overall module are elaborated. For transient contact, a calculation method based on a modified contact model was recommended strongly instead of direct measurement because of the limits of PFMD and its installation. Human kinematics statistics should be established and referred to, as operators are not static and will move around in the collaboration workspace, which will affect the safety of human–robot collision. Those suggestions will also fill the gap between the insufficient safety standards and the urgent need of collaborative robot safety evaluation.

Moreover, safety for HRC is a tripartite system. Humans, robot or/and other equipment, and the environment need to collaborate to ensure safety. Collision safety is just one of the essential issues, other factors, including properties of the material(s) to be processed, hazards from end-effector or other components, operator behaviours, shall be systematically considered in HRC system safety design and application.

Acknowledgement

This research was supported by the project "research and formulation of standards for collaborative safety evaluation and safety design of collaborative robots" (project no. 21dz2204200), funded by Science and Technology Commission of Shanghai municipality.

References

[1] ISO:8373, *Robots and robotic devices — vocabulary*, International Organization for Standardization, 2012.
[2] L. Fu, R. Wu, and J. Zhao, The evolution and enlightenment of safety specification of cooperative robots: ISO/TS 15066, *ROBOT*, *39*, 2017, 150–158. DOI: 10.13973/j.cnki.robot.2017.0532.
[3] U. Dombrowski, T. Stefanak, and A. Reimer, Simulation of human–robot collaboration by means of power and force limiting, *Procedia Manufacturing, 17*, 2018, 134–141. DOI: 10.1016/j.promfg.2018.10.028.
[4] R. Zhao and D. Sidobre, A framework for human–robot interaction in collaborative manufacturing environments, *International Journal of Robotics and Automation, 34*, 2019, 102208. DOI: 10.2316/J.2019.206-0220.
[5] P. Minyao, 2020 collaborative robot industry development blue book: Into a new era of man-machine integration!, *Gaogong Robot*, 2020, https://mp.weixin.qq.com/s/DsLhxDdrx3PwUlKsu_OtWA (accessed Jul. 15, 2021).
[6] G. Jaka, Blue book on the development of collaborative robotics industry, China: JAKA,GGII, 2019, 37–49.
[7] J.A. Falco, J.A. Marvel, and R.J. Norcross, Collaborative robotics: Measuring blunt force impacts on humans, *Proc. of the 7th International Conf. on the Safety of Industrial Automated Systems*, Montreal, QC, 2012.
[8] S. Haddadin, A. Albu-Schäffer, and G. Hirzinger, Requirements for safe robots: Measurements, analysis and new insights, *The International Journal of Robotics Research, 28*, 2009, 1507–1527. DOI: 10.1177/0278364909343970.
[9] J. Guiochet, M. Machin, and H. Waeselynck, Safety-critical advanced robots: A survey, *Robotics and Autonomous Systems, 94*, 2017, 43–52. DOI: 10.1016/j.robot.2017.04.004.
[10] L. Gualtieri, I. Palomba, E.J. Wehrle, and R. Vidoni, The opportunities and challenges of SME manufacturing automation: Safety and ergonomics in human–robot collaboration, in D.T. Matt, V. Modrák and H. Zsifkovits (eds.), Industry 4.0 for SMES: Challenges, opportunities and requirements (Cham: Springer International Publishing, 2020), 105–144.
[11] G. Industrieelektronik, The cobosafe force-pressure measurement system can check required thresold values for workplaces with human–robot collaboration, GTE Industrieelektronik GmbH, 2022, https://www.gte.de/en/messtechnik/kraft-druckmesssystem-cobosafe (accessed Sep. 10, 2022).
[12] P. GmbH, Collision measurement set PRMS for human–robot collaboration, Pilz GmbH & Co. KG, 2018, https://www.pilz.com/en-INT/products/robotics/prms/prms (accessed Dec. 4, 2022).
[13] Y.H. Li Zhihai, W. Zhenwei, and W. Hengzhi, A collision safety test system and test method for cooperative robots. CN201910484759.4, filed 23 August 2019 2019, and issued.
[14] J. Lixing, M. Fansheng, and D. Xingguang, Safety detection system of collaborative robot based on labview, *Instrument Technology and Sensors*, 2021, 54–57, 66. DOI: 10.3969/j.issn.1002-1841.2021.03.012, https://d.wanfangdata.com.cn/periodical/ChlQZXJpb2RpY2FsQ0hJTmV3UzIwMjEwNTIxEhF5YmpzeWNncTIwMjEwMzAxMhoIaWU4Y3h3Zmw%3D.

[15] N.G. Dagalakis, J.-M. Yoo, and T. Oeste, Human–robot collaboration dynamic impact testing and calibration instrument for disposable robot safety artifacts, *Industrial Robot: An International Journal, 43*, 2016, 328–337. DOI: 10.1108/IR-06-2015-0125.

[16] C. Fischer, M. Steiner, M. Neuhold, M. Papa, A. Markis, and S. Schlund, An investigation of the measurement of transient contacts in human–robot interaction, *Advances in Service and Industrial Robotics*, Cham, 2022, 547–555.

[17] ISO/TS:15066, Robots and robotic devices collaborative robots. ISO/TS 15066, International Organization for Standardization, 2016.

[18] M. Melia, B. Geissler, J. König, H. J. Ottersbach, M. Umbreit, S. Letzel, and A. Muttray, Pressure pain thresholds: Subject factors and the meaning of peak pressures, *European Journal of Pain, 23*, 2019, 167–182. DOI: 10.1002/ejp.1298.

[19] M.Y. Park, D. Han, J.H. Lim, M.K. Shin, Y.R. Han, D.H. Kim, S. Rhim, and K.S. Kim, Assessment of pressure pain thresholds in collisions with collaborative robots, *PLoS One, 14*(5), 2019, e0215890.

[20] R.G. Topazian, Pain thresholds and factors which modify them, *Oral Surgery, Oral Medicine, Oral Pathology, 10*, 1957, 1192–1203. DOI: 10.1016/0030-4220(57)90076-2.

[21] ISO/FDIS:10218-2, Robotics — safety requirements — part 2: Industrial robot systems, robot applications and robot cells, *International Organization for Standardization*, 2021.

[22] RIA, Industrial robots and robot systems—safety requirements—testing methods for power & force limited collaborative applications, Technical Report RIA TR R15.806-2018, American National Standards Institute, Washington, D.C., 2018.

[23] HSE, Collision and injury criteria when working with collaborative robots, (Derbyshire: Health and Safety Executive, 2012).

[24] ISO/IEC:17025, General requirements for the competence of testing and calibration laboratories, International Organization for Standardization, 2017.

[25] ISO:12100, Safety of machinery — general principles for design — risk assessment and risk reduction, International Organization for Standardization, 2010.

[26] 14121-2:2012, I. T. Safety of machinery - risk assessment - part 2: Practical guidance and examples of methods, 2013.

[27] T.P. Huck, N. Münch, L. Hornung, C. Ledermann, and C. Wurll, Risk assessment tools for industrial human–robot collaboration: Novel approaches and practical needs, *Safety Science, 141*, 2021, 105288. DOI: 10.1016/j.ssci.2021.105288.

[28] M. Mihelj, T. Bajd, A. Ude, J. Lenarčič, A. Stanovnik, M. Munih, J. Rejc, and S. Šlajpah, Collaborative robots. in M. Mihelj, T. Bajd, A. Ude, J. Lenarčič, A. Stanovnik, M. Munih, J. Rejc, and S. Šlajpah (eds.), Robotics (Cham: Springer International Publishing, 2019), 173–187.

[29] C.-N. Cho, J.-H. Kim, Y.-L. Kim, J.-B. Song, and J.-H. Kyung, Collision detection algorithm to distinguish between intended contact and unexpected collision, *Advanced Robotics, 26*, 2012, 1825–1840. DOI: 10.1080/01691864.2012.685259.

[30] H. Bolandi and A.F. Ehyaei, Position/force control of a dual cooperative manipulator system based on a singularly perturbed dynamic model, *International Journal of Robotics and Automation, 27*, 2012, 76–91. DOI: 10.2316/Journal.206.2012.1.206-3516.

[31] Y.Q. Yu and C.X. Zhang, Dynamic modelling for cooperation system of flexible robots manipulating a constrained object, *International Journal of Robotics and Automation, 23*, 2008, 1–8. DOI: 10.2316/Journal.206.2008.1.206-2830.

[32] N. Cobanoglu, B.M. Yilmaz, E. Tatlicioglu, and E. Zergeroglu, Repetitive control of robotic manipulators in operational space: A neural network-based approach, *International Journal of Robotics and Automation, 37*, 2022, DOI: 10.2316/J.2022.206-0654.

[33] A. Schlotzhauer, L. Kaiser, J. Wachter, M. Brandstötter, and M. Hofbaur, On the trustability of the safety measures of collaborative robots: 2D collision-force-map of a sensitive manipulator for safe HRC, *Proc. 2019 IEEE 15th International Conf. on Automation Science and Engineering (CASE),* Vancouver, BC, 2019, 1676–1683. DOI: 10.1109/COASE.2019.8842991.

[34] A. Scibilia, M. Valori, N. Pedrocchi, I. Fassi, S. Herbster, R. Behrens, J. Saenz, A. Magisson, C. Bidard, M. Kühnrich, A.B. Lassen, and K. Nielsen, Analysis of interlaboratory safety related tests in power and force limited collaborative robots, *IEEE Access, 9*, 2021, 80873–80882. DOI: 10.1109/ACCESS.2021.3085109.

[35] R.J. Kirschner, N. Mansfeld, S. Abdolshah, and S. Haddadin, Experimental analysis of impact forces in constrained collisions according to ISO/TS 15066, *Proc. 2021 IEEE International Conf. on Intelligence and Safety for Robotics (ISR)*, Tokoname, 2021, 1–5. DOI: 10.1109/ISR50024.2021.9419494.

[36] ISO:9283, Manipulating industrial robots — performance criteria and related test methods, International Organization for Standardization, 1998.

[37] R.J. Kirschner, N. Mansfeld, S. Abdolshah, and S. Haddadin, ISO/TS 15066: How different interpretations affect risk assessment, 2022, *arXiv:2203.02706*.

[38] DGUV, Project no. Ff-fp 0317: Experimental assessment of pain thresholds in major parts of the human body due to mechanical exposure in human–machine interface, 2014, https://www.dguv.de/ifa/forschung/projektverzeichnis/ff-fp0317-2.jsp.

[39] D.G. Unfallversicherung, BG/BGIA risk assessment recommendations according to machinery directive design of workplaces with collaborative robots. October 2009 edition, revised February 2011.

[40] Y. Yamada, K. Suita, H. Ikeda, N. Sugimoto, H. Miura, and H. Nakamura, Evaluation of pain tolerance based on a biomechanical method for human-robot coexistence, *Transactions of the Japan Society of Mechanical Engineers, Series C, 63*, 1997, 281–2819.

[41] ISO10218-1:2011, Robots and robotic devices — safety requirements for industrial robots — part 1: Robots, ISO, 2011.

[42] I. Daniyan, K. Mpofu, F. Ale, and M. Oyesola, Design and simulation of a dual-arm robot for manufacturing operations in the railcar industry, *International Journal of Robotics and Automation, 36*, 2021.

[43] IEC, Safety in the future.

[44] UR, Cobots offer game changing benefits, 2023, https://www.universal-robots.com/uk/collaborative-robots-cobots-benefits/ (accessed May 28, 2023).

[45] V. Gopinath and K. Johansen, Risk assessment process for collaborative assembly – a job safety analysis approach, *Procedia CIRP, 44*, 2016, 199–203. DOI: 10.1016/j.procir.2016.02.334.

[46] M. Askarpour, D. Mandrioli, M. Rossi, and F. Vicentini, SAFER-HRC: Safety analysis through formal verification in human-robot collaboration, *Proc. Computer Safety, Reliability, and Security*, Cham, 2016, 283–295.

[47] S.-D. Lee, B.-S. Kim, and J.-B. Song, Human–robot collision model with effective mass and manipulability for design of a spatial manipulator, *Advanced Robotics, 27*, 2013, 189–198. DOI: 10.1080/01691864.2012.754076. https://www.tandfonline.com/doi/full/10.1080/01691864.2012.754076.

[48] R.J. Kirschner, N. Mansfeld, G.G. Pena, S. Abdolshah, and S. Haddadin, Notion on the correct use of the robot effective mass in the safety context and comments on ISO/TS 15066, *Proc. 2021 IEEE International Conf. on Intelligence and Safety for Robotics (ISR)*, Tokoname, 2021, 6–9. DOI: 10.1109/ISR50024.2021.9419495.

[49] HEXAGON, Leica absolute tracker at960, HEXAGON, 2022, https://hexagon.com/products/leica-absolute-tracker-at960?accordId=5EFAEE4F75B3447290896B712CEEE29E (accessed Nov. 20, 2022).

[50] ISO:13855, Safety of machinery — positioning of safeguards with respect to the approach speeds of parts of the human body, *International Organization for Standardization*, 2010.

[51] Instruction, O. 29 CFR 1910.217 mechanical power presses, clarifications, STD 01-12-021, *Occupational Safety and Health Administration*, 1978.

Biographies

Xiaopeng Zhu , received the bachelor's degree from Southeast University in 2010, followed by the master's degree from Shanghai Jiao Tong University in 2013. Currently, he is pursuing the Ph.D. degree with Shanghai Jiao Tong University with a focus on advanced manufacturing since 2018. From 2013 to 2016, he worked as a Robot R&D Engineer with the Central Research Institute of Shanghai Electric Group Co., Ltd and Shanghai Jiao Tong University, primarily involved in the development of mobile robot products and applications for robot welding. Since 2016, he has been serving as the Vice Manager of China National Robot Test and Evaluation Center (Headquarter) for Shanghai Electrical Apparatus Research Institute (Group) Co., Ltd. His research interests encompass various aspects, such as robot safety, performance evaluation, and adaptability across different application scenarios.

Ke Zhang , Professor, received the master of engineering degree from Xi'an Jiaotong university in 2001, and the Ph.D degree from Shanghai Jiaotong University in 2005, and then become a Teacher with Shanghai Jiaotong University, and stayed in the BIAS Institute of Bremen University in Germany as a Visiting Scholar at 2008.11-2009.1, and stayed in the ISM institute of University of Kentucky in the United States as a Visiting Scholar in 2016.3-2017.3. His research interests mainly include robotic technologies, process control and automation for laser welding technology. Won Second Prize for Science and Technology Progress Award of Chinese shipbuilding industry Ministry, First Prize and Third Prize of science and technology progress award for Chinese Machinery industry Ministry, and Second Prize and third Prize of shanghai science and technology progress award, achieved more than 30 national invention patents, published more than 50 papers.

Xueming Hua , Professor, Director of Institute of Welding and Laser Manufacturing, School of Materials Science and Engineering, Shanghai Jiao Tong University, IIW C-XII delegate, Chairman of Shanghai Welding Society, published more than 200 papers, authorized more than 30 national invention patents, main research interests include welding arc physical and efficient welding new methods, robot welding technology and intelligent equipment.