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Analysis of Interlaboratory Safety Related Tests in Power and Force Limited Collaborative Robots

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ABSTRACT The use of collaborative robots in the industrial domain has significantly grown in the last years, allowing humans to operate in the same workspace occupied by robots without any physical barriers. Understandably, the safety of the human operator has been a major concern both for researchers and regulatory bodies. The power and force limited modality of robots is of particular interest in that sense, being used in order to bound the energy of eventual collisions when a close physical interaction with humans is necessary. Such an interaction modality allows the robotic system to operate without the use of barriers, but a measurement of the force and pressure occurring due to a contact must be provided as part of the risk assessment. However, the precise procedure to follow in order to reliably provide such measures is still unclear for users and system integrators willing to self-assess the safety of their own collaborative robotic system. In this work, the repeatability and reliability of such testing procedures and measures are analyzed with an interlaboratory comparison approach, with the aim to establish the degree of variability possibly encountered when performing the same test under slightly different conditions.

INDEX TERMS Industrial robot safety, human-robot collaboration, cobot, power and force limitation, interlaboratory comparison.

I. INTRODUCTION

In the industrial sector, the number of workplaces where people work in proximity to or even cooperate with robots has significantly increased over the last few years [1], [2]. Some applications require robots to work in the same shared workspace with the human operator for the entire duration of the process. During such work processes, there is a risk of collisions between humans and robots [3].

In order to be distributed and used in Europe, a programmable robotic system must comply with the Machinery Directive 2006/42/EC [4] and be provided with an EC Declaration of conformity. The specific requirements for industrial robots and robotic systems are illustrated in the ISO technical standards 10218-1 [5] and 10218-2 [6]. However, the aforementioned standards do not comprehensively describe the requirements of collaborative robotic applications. This led to the development of a most recent technical specification on the use of collaborative robots on the industrial domain, which is ISO/TS 15066:2016 [7].

The aforementioned standard describes 4 different interaction modalities in a collaborative robotic system [8]:

- Safety-rated monitored stop (SRMS): robot system is in the collaborative workspace, the safety-rated monitored function is active and robot motion is stopped, the operator is permitted to enter the collaborative workspace;
- Hand guiding (HG): The operator uses a hand-operated device to transmit motion commands to the robot system;
- Speed and separation monitoring (SSM): during robot motion, the robot system never gets closer to the operator than the protective separation distance;
- Power and force limiting (PFL): physical contact between robot system, contact events between the

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collaborative robot and body party of the operator could come about a number of ways - e.g. intended or incidental contact.

The embedding of the interaction model within the safety rules that run on robot controller has been investigated recently. For example, [9] proposes a fuzzy-impedance controller with embedded safety rules in collaborative industrial applications, while in [10] the interaction model was used in combination with learning from demonstration techniques. In general, over the past two decades, safety and reliability of robots have been the subject of intense research efforts. Such efforts have been directed on all fronts to ensure the emergence of safer and more reliable robotic systems. These works address a wide range of issues ranging from robot safety in terms of safe equipment and workplace design [11], [12] [13], to human factor considerations [14], including legal aspects related to robot technology [15]. Other investigations, such as [16], have focused on providing standard safety measures for testing, inspection, installation and maintenance of robots. In [17] the problem of measuring the effectiveness of the safety measures was taken into account.

The European project COVR [18], also named "being safe around collaborative versatile robots", to which this work belongs, has the main purpose of reducing complexity in safety validation of collaborative robotic applications, bridging the gap between available standards and the emerging needs of final users. This is done by investigating all those aspects which still create uncertainties for users in the application of directives and standards in their specific domain. On a general basis, these aspects can be linked to the difficulties in the identification of safety requirements in a specific domain of application, or to the lack of practical testing procedures to execute in order to assess the fulfilment of such requirements in a collaborative system. There is, indeed, a need for practical guidance for manufacturers, system integrators, users and certification bodies on how to perform these measures having at the same time both a slim testing procedure and reliable results.

With reference to the four interaction modalities described by the standard [7], this paper focuses on PFL and, in particular, on the assessment of unintended collisions between human and robot, which stands as the most hazardous occurrence in human-robot collaboration (HRC). With regard to this, there is currently a consolidation of testing procedures aimed at reproducing the contact scenarios by substituting the human with specific sensors with body-like features for the evaluation of force and pressure. Considering that this kind of test is expected to become a well-established best practice in the assessment of contacts during HRC, it is worth observing that there are several factors which may influence test results, beyond the mere human-robot mutual positions and velocities. For this reason, in this work an interlaboratory comparison approach is used in the analysis of testing procedures and measures concerning the safety of a collaborative robotic system in relation to the occurrence of unintended contacts with the operator. The scope of the work is to assess the degree of repeatability of such testing procedures and identify the testing conditions which may lead to untrustworthy results, with the final aim of minimizing the sources of error.

A. POWER AND FORCE LIMITATION

Power and force limitation (PFL) has become one of the most commonly used safety measures in industrial best practice, aimed at preventing injuries and limiting the risk level of any identified hazard related to the accidental contact between parts of the collaborative robotic system and the operator. According to this, a first consideration in the risk assessment is to determine the exact parts of operator body and robot structure which will likely be involved in such contacts, as well as the state of the robot (i.e. configuration and velocities) when the contact can occur. This is crucial, since different areas of the human body are characterized by different thresholds to resist the biomechanical load without incurring minor injuries. For the purposes of this specification, a body model has been proposed in [7], including 29 specific body areas classified in 12 body regions. Figure 1 shows the contact areas in the body model, while Table 1 shows the specific labels of each body position, classified into general body regions and designated as located in the front or back of the body. For each body part, the biomechanical limits have been established in terms of maximum force and pressure allowed.

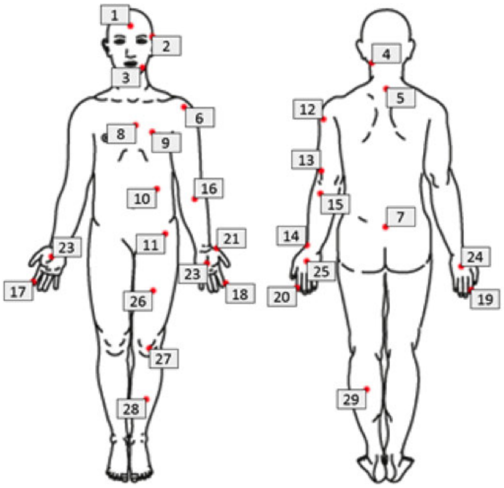


FIGURE 1. Body model as described in [7], each specific body location considered within the model is associated with a label from 1 to 29.

These values are the result of a study conducted by the University of Mainz on the levels of onset of pain [19]. The transferred energy, resulting from the hypothetical contact between robot and human body, is modeled based on these force and pressure thresholds and assuming a completely inelastic contact; robot speed limits are obtained for each body region potentially involved in the collision, depending on the effective moving mass. When the risk of accidental contact emerges from the risk assessment of a collaborative robotic application, two types of risk reduction measures (RRMs) can be considered:

TABLE 1. Scheme of the impact thresholds for each specific labelled body location, and its relative body region, according to [7]. Pressure and Force thresholds are indicated for quasi-static (QS) contacts; for each value, the correspondent threshold for a transient impact can be calculated by multiplying by two. Values marked with an asterisk are referred for transient contacts only, while QS contacts should never occur.

Label	Location	Body Region	Pressure $[\mathrm{N/cm^2}]$	Force $[\mathrm{N}]$
1	Centre of forehead	Skull and forehead	130*	130*
2	Temple	Skull and forehead	110*	130*
3	Masticatory muscle	Face	110*	65*
4	Neck muscle	Nape	140	150
5	Spinous process (7 th ver.)	Nape	210	150
6	Shoulder joint	Back and shoulders	160	210
7	Spinous process (5 th ver.)	Back and shoulders	210	210
8	Sternum	Chest	120	140
9	Chest muscle	Chest	170	140
10	Abdominal muscle	Belly	140	110
11	Pelvic bone	Pelvis	210	180
12	Deltoid muscles	Upper arm and elbow	190	150
13	Upper arm bone	Upper arm and elbow	220	150
14	Spoke bone	Underarm and wrist	190	160
15	Forearm muscle	Underarm and wrist	180	160
16	Arm nerve	Underarm and wrist	180	160
17	Forefinger berry dominant	Hand and finger	300	140
18	Forefinger berry not dominant	Hand and finger	270	140
19	Forefinger joint dominant	Hand and finger	280	140
20	Forefinger joint not dominant	Hand and finger	220	140
21	Thenar prominence	Hand and finger	200	140
22	Palm dominant	Hand and finger	260	140
23	Palm not dominant	Hand and finger	260	140
24	Back of the hand dominant	Hand and finger	200	140
25	Back of the hand not dominant	Hand and finger	190	140
26	Thigh muscles	Thigh and knee	250	220
27	Kneecap	Thigh and knee	220	220
28	Shin	Shank	220	130
29	Calf muscle	Shank	210	130

- active technical protective measures in the robot system, such as tactile safeguards, torque sensors, force sensors, speed and range limits.
- passive protective measures, like adapting the shape of the robot, its gripper, the tool, workpiece, and of all other devices involved in the work process; applying protective materials on one or more parts of the robot (skins); ensuring passive compliance in the design stage.

With the PFL function, collaborative robots can even be used without conventional safety and protective devices, such as fences and light curtains. In other application cases, in which the implementation of other external safety measures is provided, this functionality further reduces the residual risk. In order to assess and validate risk reduction, a measure of the load arising in critical collision processes must be provided.

Relevant research efforts have been done towards a precise and reliable estimation of external forces by the robot in PFL modality, in order to improve its collision detection capability. In [20] for example, the authors propose a methodology for the estimation of forces and currents in each robot joint for a given trajectory, using a dynamic time-invariant model in combination with Artificial Neural Networks. The computed predictions are used to limit the current to a user-defined threshold. Other sensorless approaches to improve robot's collision detection capability were proposed in [21] and [22]. Although these techniques are promising, they are mostly useful to trigger post-impact strategies, rather than preventing possible collisions/impacts. The current best practices for the assessment of the residual contact risk rely on the performance of impact tests to determine whether the whole system complies with the aforementioned biomechanical limit values. This is done by reproducing the possible impact configurations, robot system state and conditions as identified in the risk assessment. Accordingly, such testing procedures should be performed using a biofidelic, i.e. biomechanically humanlike, measuring instrument (see Figure 2). In connection with the current revision of the standards for industrial robots, the German Institute for Occupational Safety and Health (IFA) has defined new safety requirements specifically for the biomechanical/medical stressing of humans in collisions [23]. These recommendations also refer to the methodology for testing the individuated contact scenarios, including sensor type and configuration for the simulation of the different body parts (i.e. damping material Shore hardness, thickness and spring constant) and similar information is provided in the ANSI RIA TR 15.806 [24]. The revised ISO 10218-2 [25], currently under evaluation as a Draft International Standard, is consistently updated concerning HRC and new Annexes incorporate the approach for pressure and force measurements in PFL applications, as well as the information provided in the ISO TS 15066. In the online COVR Toolkit [26], several testing protocols for the validation of HRC applications are made available and some of these refer to the systematic assessment of force and pressure in potential collision between human and robot, identified with the safety skill "Limit Interaction Energy". They are categorized considering the type of contact, which can be "transient" or "quasi-static", and the type of robotic devices, as it is argued that even the assessment of rehabilitation robots can benefit from analogue testing procedures [27].

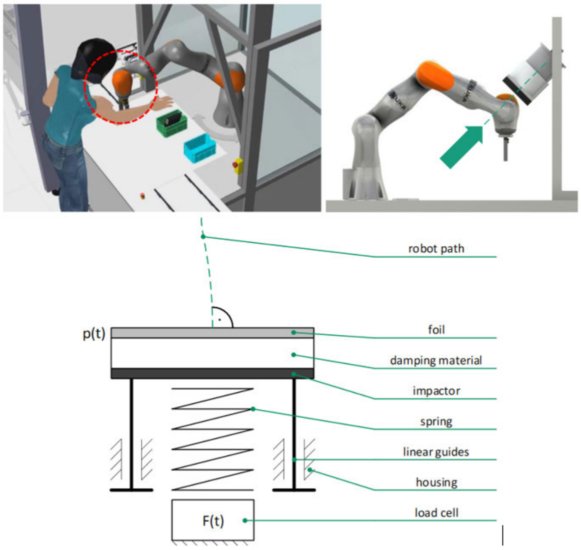
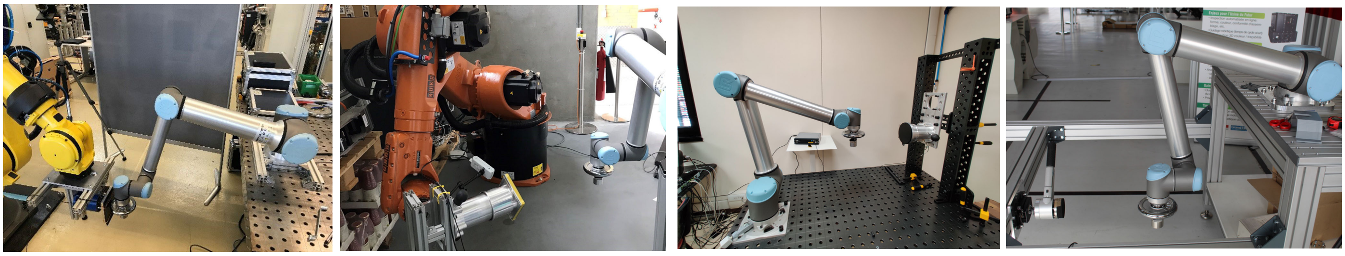


FIGURE 2. Figures taken from the ROB-LIE-1 COVR Protocol, representing respectively: an example of collision hazard identified by the risk assessment on the top left corner, the corresponding test setup on the top right corner, and the architecture of a biofidelic sensing device at the bottom.



(a) IFF (b) DTI (c) CNR (d) CEA

FIGURE 3. **Experimental setups in the four different research labs participating to the described collision tests, with the robot on the right side of figures 3a, 3b and 3d, and on the left side in 3c. The sensor used to measure the impact force is hold by an high payload industrial robot in 3a and 3b, in 3c is fixed in a welding table, and in 3d in an aluminium profile.**

B. PAPER CONTRIBUTION

The interlaboratory performance comparison is an integral part of best-practices of most general laboratory quality control systems [28], and the range of application for this kind of procedures varies from the chemical industry, to medicine [29] and robotic systems. In particular, the aims of characterizing and assessing collaborative robotics tasks lead, in some cases, to the necessity of the involvement of third parties as accredited measuring labs, reliable in accordance to the ISO IEC 17025 [30].

The comparison approach proposed in this work aims at identifying the possible discrepancies which may occur in testing the same contact scenario of a HRC task. The design of test setup used in this work was based on these considerations and requirements, with the purpose of identifying any possible source of variation, and possibly quantifying its contribution within the obtained results. Four European research centers, partners of the project, performed the test procedure individually: the National Research Council of Italy (CNR), The Fraunhofer Institute for Factory Operation and Automation (IFF), the Danish Technological Institute (DTI), The French Alternative Energies and Atomic Energy Commission (CEA). Aiming at a detailed analysis, several robot motion trajectories and impact points were set; in the setups implemented by each of the partners, the kind of robot, type of measuring instrumentation, motion programs and test configuration were standardised, aiming at simulating the case of testing specific contact scenarios by applying the most general testing procedures. The only exceptions were the following two aspects: robot controller and sensor fixture. In fact, the available procedures do not provide prescriptions for these parameters, which can both influence the energy transferred during the impact in different ways, as will be discussed in Section III.

Accordingly, this variability between the labs set-up can be considered as pragmatically representative of conditions possibly encountered by roboticists and stakeholders attempting to autonomously perform this task. The main aim of this strategy is to observe whether using the same robot and sensor and reproducing the same dynamic contact scenario is sufficient to guarantee test reliability, or, otherwise, whether it is necessary to take into account other relevant parameters. Section II describes the setup of the tests and the methodology observed, while influence of such variations on the results is discussed in detail in Section III.

II. MATERIALS AND METHODS

The experimental setup and methodology used in this work relies on the biofidelic measuring instrumentation described in [31]. The measuring instrument used replicates the deformability of a human body part, modeling it as a mass-spring-damper system, to which parameters can be clearly assigned.

This force/pressure measuring sensor is meant to be used for assessing the external overall collision force in a variety of practical industrial applications, and thus appears to be suitable for the purpose of this work.

A. SETUP

Each laboratory was equipped with either "*GTE Kolrobot 300N*" or "*GTE CBSF-75 Basic*" force measuring sensors, and with "*TekScan I-Scan*" or "*FUJI foils*" for pressure measurements, each instrumentation included an analysis software. All the labs used the same robot "family" (UR10(e) from Universal Robots).

The experiments were performed considering body location 8 (sternum), body location 10 (abdomen) and body location 25 (back of the hand), labelled according to the schematization illustrated in Figure 1, which were considered as the most probable locations possibly subject to an impact during a collaborative task. The used sensors approximate these body regions as a mass-spring-damper system [31], as illustrated in Figure 2. Spring stiffness was set to respectively to 10N/mm, 25N/mm and 75N/mm for reproducing the abdominal region, sternum and hand [7]. In the "contact area" on the surface of the sensing system, a damper material of hardness SH70 was used for sternum and hand, and SH10 for the abdominal region.

For the purpose of this analysis, the "*transient contact*" thresholds, as indicated in [7] and shown in Table 1, were taken into account in the final evaluation of the measured force signals (Section III). The highest peak of each force signal was compared with the corresponding threshold. The reason for this choice is to be found in the variability of factors such as the stopping time of joint brakes and their elasticity, which can determine whether the body region is subject to

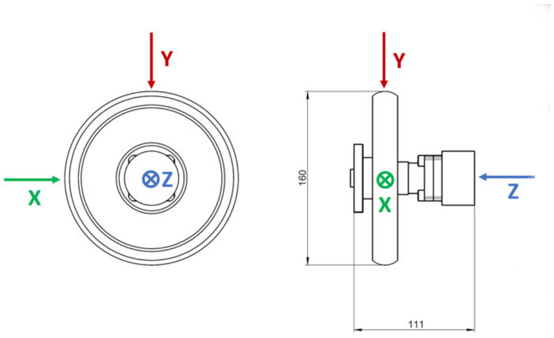


FIGURE 4. Structure of the designed tool applied in the end-effector of the robot for collision testing. The axes x,y,z originate, in the tool surface, from the three contact points mentioned in Table 3, being respectively C_1, C_2, and TCP.

TABLE 2. Description of the test parameters in terms of: physical features of the tool applied on the robot end-effector and safety settings on the robot controller.

Parameters	Description
Mass of the tool	3.3 kg
Safety functions **UR10e**	Power: 300 W Momentum: 25 N m Stopping time: 400 ms Stopping distance: 500 mm TCP speed limit: 1500 m/s TCP force limit: 150 N Elbow speed limit: 1500 m/s Elbow force limit: 150 N
Safety functions **UR10**	Power: 300 W Momentum: 25 N m TCP speed limit: 1500 m/s TCP force limit: 150 N

"*quasi static*" compression after an impact with the robot or not, and the detected force after an impact [32], [33] [34]. Considering only the peak of the force signal allows us to eliminate the influence of the aforementioned aspects from the obtained measures and also to extend their applicability to different types of robots than the ones used in this work.

The values in the force curves relative to the nominal spring rate 75N/mm were considered with respect to the hand threshold (280N).

The robot itself is expected to be the main source of variability in these impact tests. Differences in the used robot models or versions, despite coming from the same manufacturer, could have a great influence on their behavior after an impact, for example in terms of reaction time of joint brakes. In order to determine the influence of the robot controller and hardware structure on the results, two slightly different versions were used in this trials: UR10 and UR10e.

Figure 4 represents the structure of the tool mounted at the end-effector of all the robots and its main geometrical features. Its mass is detailed in Table 2, and its orientation was set with the z' axis of the tool frame directed in the negative vertical direction (w.r.t. robot base frame).

Table 2 also details the safety settings in each robot controller; these settings restrict maximum allowed power, momentum, and force limits in the tool center point (TCP). Also the speed limits were set to the maximum values detailed in the table, in order to ensure that the robot reaches its target speed during the motion.

B. METHODOLOGY

For contact evaluation, apart from the force and pressure values over time, the robot states were also saved in order to monitor the robot controller variables during the collisions. In particular, referring to the Universal Robots' data exchange interface, robot states are expressed as: joint positions, velocities and currents; forces in the Tool Center Point (TCP); Cartesian coordinates (position and orientation vectors (x, y, z, r_x, r_y, r_z)) of the tool; and speed of the tool (also in Cartesian coordinates).

The impact force and pressure were recorded in four joint configurations, corresponding to four different positions of the TCP inside the operational volume where an impact between human and robot is more likely to occur. These points of measure are represented in Figure 5 as M_1, M_2, M_3 and M_4. The percentages in Figure 5 indicate how the four points of measure are computed and distanced. If max_x is the maximum possible extension of the robot along its x-axis (according to robot base frame) in which the tool can be positioned with its z'-axis along the negative vertical direction, M_1 and M_4 are respectively at 66% and 33% of max_x. While M_2 and M_3 are considered to be at 33% with respect to M1 along its positive and negative vertical direction.

The impact occurred in the four points of measurement with three types of movements which are commonly the most likely to be executed by the robot in a collaborative task:

- x^+, rotation around base link
- y^+, linear movement along y axis
- z^+, linear movement along the vertical axis

where axes are referred with respect to robot base frame, every movement started 300 mm before the considered impact point if linear, and 30° if rotational. These points and motions, corresponded to four different configurations of the robot joints. For each point of measure and motion trajectory, the velocity in which the motion was executed was varied starting with value of 50mm/s and increasing it in increments of 50mm/s for each test. The final value was set to 450mm/s, or to the value in which the resulting force overcame the body sensor's saturation limit. The total number of tests was 1456 for the three considered body locations. The robot was rigidly fixed on a table, whose mass and stiffness can be considered infinite for the purpose of this analysis, while the sensor was held in four different ways:

- Industrial robot, with 60kg payload
- Industrial robot, with 165kg payload
- Aluminium profile
- Welding table

An overall description of the five experimental setups used by the four participating research institutes is summarized in Table 4, where the differences in terms of robot controller, spring and damper materials, and sensor fixtures are

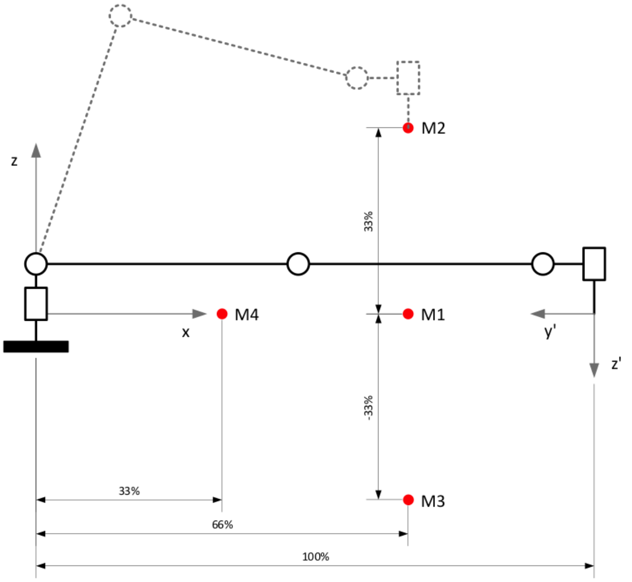


FIGURE 5. Schematic representation of the test setup. The four points of measure were computed as follows: M1 and M4 were respectively the 66% and the 33% of the robot maximum extension along x-axis (with respect to its base frame), while M2 and M3 were obtained adding to M1 position a 33% displacement along positive (M2) and negative (M3) z-axis direction.

TABLE 3. Summary of the different types of tested configurations. For each point of measure in which the sensor was placed (M_1 to M_4) three different movements were executed along the axis x,y, and z. This lead to a total number of 12 tests for each velocity setting.

No	Test Point	Collision Direction	Motion	Contact Point	Pressure Scan
ID1	M_1	+x'	PTP	C_1	NO
ID2	M_1	-y'	LIN	C_2	NO
ID3	M_1	+z'	LIN	TCP	YES
ID4	M_2	+x'	PTP	C_1	NO
ID5	M_2	-y'	LIN	C_2	NO
ID6	M_2	+z'	LIN	TCP	YES
ID7	M_3	+x'	PTP	C_1	NO
ID8	M_3	-y'	LIN	C_2	NO
ID9	M_3	+z'	LIN	TCP	YES
ID10	M_4	+x'	PTP	C_1	NO
ID11	M_4	-y'	LIN	C_2	NO
ID12	M_4	+z'	LIN	TCP	YES

specified. For the body location 25 (back of the hand) a total number of 423 tests was carried out. Due to the high number of tests to be performed, it was chosen to repeat the measurement three times only for the highest possible velocity.

III. RESULTS ANALYSIS

Impact forces measured when performing the tests in the 12 joint configurations appeared to have very similar trends in most cases, although some variations can be noticed in a significant number of tests.

TABLE 4. Comparison among the experimental setups used from the four research institutes participating to the experiments.

Setup	A	B	C	D	E
Institute	1	2	3		4
Robot	UR10	UR10	UR10	UR10e	UR10e
Nominal spring rate $\mathrm{N/mm}$	75	75	75		75
Measured spring rate $\mathrm{N/mm}$ (gradient between $100\ldots300\,\mathrm{N}$)	65	68	67		72
Damper	SH70	SH70	SH70		SH70
Measurement Device	Kolrobot-500 N	IFA Kolrobot-1000 N	CBSF-75-Basic		GTE-1000N
Sensor Fixture	Welding Table	Robot-$165\,\mathrm{kg}$	Aluminium profile		Robot-$60\,\mathrm{kg}$

The first known parameter that affects the measured impact force is the velocity: Figure 6 shows the behavior of force over velocity for x, y and z direction, for body location 25, respectively in the first, second and third row. Columns represent the four joint configurations. It was observed that generally the collision force varies linearly with velocity, but not with a proportional relation, as predicted by the simple inelastic model described in ISO/TS 15066:2016. Instead, a force offset is evidenced in all the curves in Figure 6, indicating that the robot would apply a force to the object/person at low velocities. In these collaborative tests, high velocities were not reached, since the tests were stopped if the limit value of the specified body part were exceeded.

In order to highlight more this aspect, the force collision tests were used to determine the maximum speed which ensures that the maximum force reached during the impact, remains below the limits defined in ISO/TS 15066:2016. Box plots in Figure 7 show the variance in the value of maximum velocity obtained for all the 12 tested configurations below the force limit of 280 N. Indeed in most cases, such as: configuration 1 for impact direction x; configurations 3 and 4 for impact direction y; and configuration 1 and 4 for direction z, the range of values observed from all the five setup types were very similar. Nevertheless, important exceptions are evident, like in joint configuration 2 and impact direction y, which corresponds to test ID5 according to Table 3, where the observed range of velocities is very wide.

If looking at configuration ID5 in Figure 6, the same consideration can be confirmed, being the test configuration in which the maximum offset can be observed between the five force-velocities curves. In particular, ID5 is the tested configuration in which the maximum moment arm between the collision force and the weakest robot axes is minimum. This means that an identical collision force would produce less perturbing torque at joints, and also makes the results more sensitive to small positioning differences. This suggests that the measured force can be influenced by the distance between the collision point and the robot base frame. This aspect was investigated in other research works [35], in which the variation of the measured impact force over the distance is studied for various velocities of the robot, and is confirmed by these evidences. By looking at both Figures 7 and 6, it can be noticed that in impact direction y, corresponding to an extension movement of the robotic arm, where the distance between the tool and robot base frame increases over time, the variability between the results is averagely more

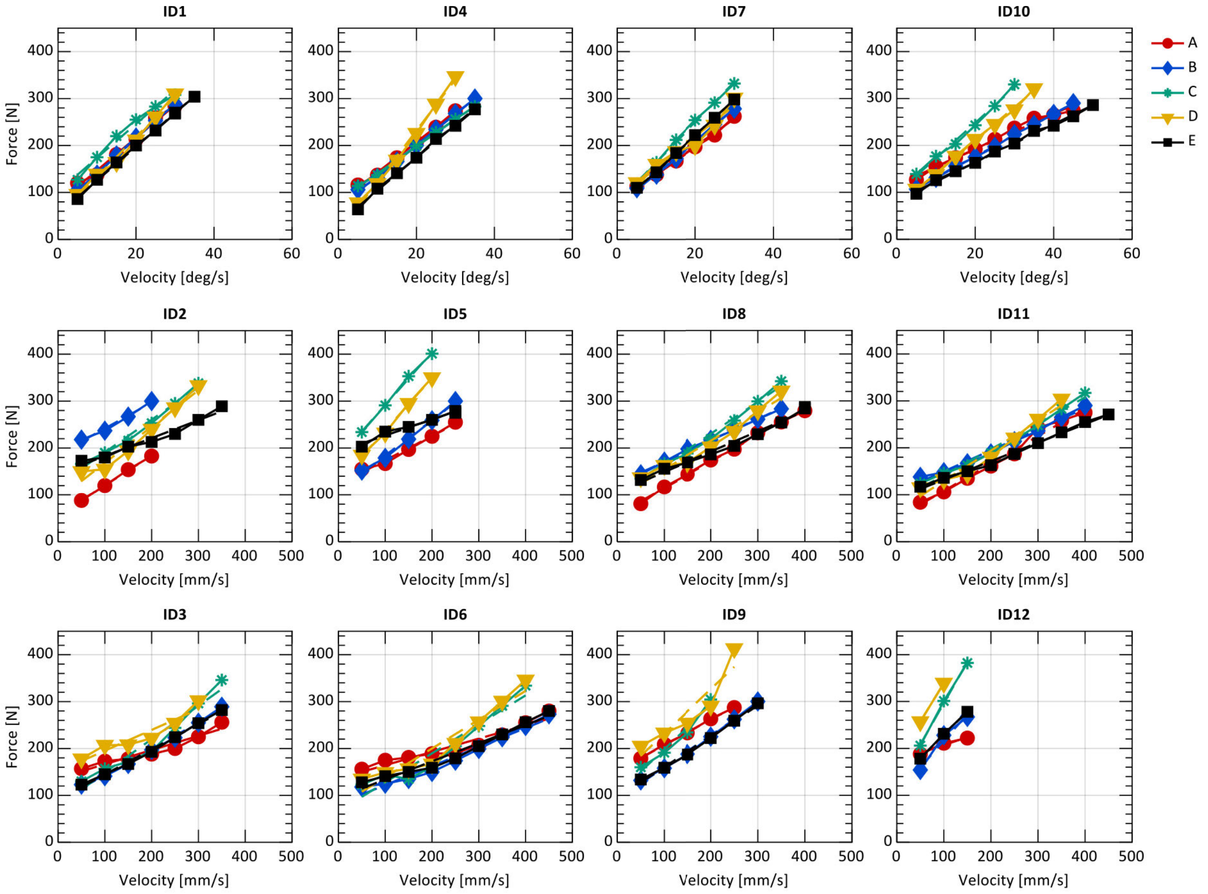


FIGURE 6. **Plots representing the behavior of force over velocity relative to the impact tests performed with body location 25 (back of the hand), for all the five setup types, indicated according to the nomenclature detailed in Table 4. Each column (e.g. ID1 to ID3, ID4 to ID6, etc.) represents a joint configuration, while rows represent the three collision directions.**

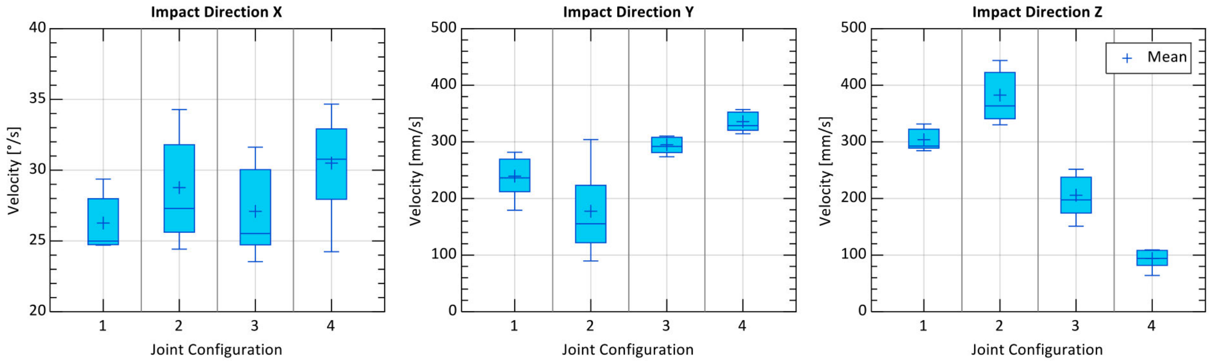


FIGURE 7. **Box plots representing the maximum admissible velocity, derived from the collision tests for the 12 testing configurations with spring 75**$\mathrm{N/mm}$ **and damper SH70, whose corresponding impact force stays below the limit of** $280\,\mathrm{N}$ **established from ISO/TS 15066:2016.**

relevant if compared to those obtained from impact direction x (rotation around base link), where this value is constant. In general, Point To Point motions (the ones directed along positive x axis) presented a typical variety of $5°/s$, with a maximum of $25°/s$. Linear movements (y and z axis) were averagely more critical, with a typical variety of $50\mathrm{mm}/s$ and maximum values up to $200\mathrm{mm}/s$.

On the other hand, on the sensor side, the influence of the variation of the total stiffness on the measured force was also taken into account. The total stiffness of the system is given by the sum of the two contributing factors derived from the stiffness of the spring used inside the sensor and the stiffness of the fixture. With regards to the spring stiffness, spring constants were measured in order to determine the deviation from their nominal value, as indicated in Table 4. Relatively significant differences were observed in some cases. Moreover, the used fixtures had in turn very variable stiffness, ranging from a 60 kg payload industrial robot to welding table. It is known that both aspects may potentially have an influence on the measured force, as illustrated in [36] and [23]. Despite this, looking at the results is evident that in the majority of cases both spring constant and fixture type seemed to have limited effects on the variability of measured force signals.

However, in configurations where the maximum distance between the robot tool and the base frame was highest, the effect of sensor fixturing was more influential on the variation of impact energy. In the end, another critical aspect of the performed tests was the pressure measurement, which proved to be difficult to be replicated in a reliable way by an end user. The obtained results appeared to be very sensitive to movements of the robot, the cylindrical shape of the tool (Figure 4) caused high pressure on its edges, that maximized the errors due to small misalignments.

IV. CONCLUSION

The presented work deals with the reliability of impact assessment tests for the safety validation of collaborative robotics applications. Considering a pre-defined set of impact configurations, the same tests were performed in four different laboratories, simulating the assessment of hypothetic ''quasi-static'' human-robot contact scenarios. The tests were performed according to the state-of-the-art testing procedures for collision testing in robotic applications characterized by PFL [23], [24], [26]. A first remark is related to confirming the necessity of testing the potential impact scenarios identified by the risk assessment replicating the real configurations, as robot state and human-robot (or, sensor-robot) mutual positions are fundamental variables of the assessment. Therefore, the testing procedures need to be repeated by users whenever there are changes in such conditions, thus limiting in practice the flexibility of collaborative robotic applications. Although the majority of tests resulted in reliable measurements, in some cases the actual resulting values seemed to be quite sensitive to the variability of the experimental conditions, even using commercially available testing sensors co-developed with IFA [31]. Such variability occurs in particular combinations of robot-sensor configuration and type of movement, which can be related, conversely, to the scenarios in which the distance between robot base and impact location was at maximum. The analyzed results showed that the most critical boundary conditions to focus on are robot controller and sensor fixture.

Considering the robot controller, since variations on the exerted force were observed in different configurations and types of movement, the general validity of such testing procedures is still in question, limiting in practice the flexibility of collaborative robotic applications. Despite this, for an end-user performing the assessment test in a specific collaborative application, the same controller of the real robotic application is supposed to be used. Under this premise, it can be considered a minor issue.

In relation to sensor fixture, it is worth observing that reproducing a specific contact scenario can require particular setups, which may introduce some uncertainties in the test, consequently affecting the repeatability. This paper highlights the relevance of realizing effective setups when dealing with this kind of tests, warning about the necessity of a preliminar evaluation of the overall stiffness of the structure. Accordingly, in the current revision of the ISO 10218-2 [25], it is prescribed that the used sensor ''is to be fixed and secured on a solid base having as much rigidity as practicable''. The open question concerns whether it would be necessary to provide more strict indication in relation to this aspect, possibly indicating some reference stiffness values.

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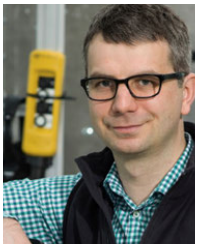

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