Collaborative Robotics: Measuring Blunt Force Impacts on Humans

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ABSTRACT

Robot manufacturers are developing a new generation of industrial robots that are designed to work in collaborative environments in close proximity to humans. In parallel, an international standards effort is developing a technical specification to support a new set of robot safety standards that include provisions for collaborative robot operation. As these two developments merge, industry needs measurements and test methods to determine if this new generation of robots conforms to the emerging collaborative robot safety standards. Furthermore, the standards effort is in need of measurement implementations to validate the proposed collaborative metrics. Power and force limiting, one aspect of the evolving safety standards, is a robot function that performs a protective stop if any force or pressure limit is exceeded when a robot makes contact with a human during collaborative operations. The standard defines a set of injury metrics based on predetermined medical/biomechanical requirements and parameters. These parameters and requirements include a defined human body model with main and subcomponent regions, relevant injury criteria with per-region limit values, and characteristic values for the deformation constants for the established body regions. These permissible forces and surface pressures for the affected individual body regions must be tested according to potential collision area points after setting up a collaborative robotic workcell. This paper provides an overview of the injury metrics currently proposed, and describes a prototype measurement device that replicates the deformation constants of the various body regions and measures static and dynamic collision forces during robot collisions. Initial testing of the device is presented along with evaluation of the metrics currently proposed by this standards activity.

1 INTRODUCTION

A new class of robots is emerging that are fundamentally different from classical industrial robotics [1,2]. Traditional industrial robots are designed to achieve positioning accuracy with high repeatability, high speed, and stiffness. These performance characteristics, however, result in massive robots in comparison to their rated payloads, and may have a load-to-weight ratio on the order of 1:10. Newer robot designs are smaller and use lighter materials to achieve load-to-weight ratios closer to 1:1, but at the expense of having lower payload capacities and lower stiffness. These next-generation robots, although still largely only in prototype stages, are lighter, safer, and easier to deploy and reconfigure, effectively making them ideal for deployment in collaborative manufacturing environments.

A barrier to widespread adoption of these collaborative robots in manufacturing, however, is the lack of performance standards certifying their safety when working with humans. The established national and international standards provide minimal guidance for collaborative robotics, providing only names for the types of collaborations that are permitted.

The latest release of the ISO 10218 industrial robot safety standards [3,4] has requirements for addressing collaborative robot safety in the areas of:

- Speed and Separation Monitoring (SSM): a robot system function that maintains a safe operation distance from humans located in a collaborative workspace, and
- Power and Force Limiting (PFL): a robot system function that performs a protective stop if any force or pressure limit is exceeded when a robot makes contact with a human during collaborative operations.

The ISO TC184/SC2 WG 3 standards committee on safety of industrial robots is currently working on technical specification TS 15066 to provide additional guidance in the areas of SSM and PFL modes of robot collaboration [5]. As part of the PFL efforts, injury severity criteria are being developed to establish maximum forces that a robot can impose on a human during a collision. This paper describes the National Institute of Standards and Technology (NIST) effort to develop a measurement device to assess the ability of an industrial robot system to stay below the defined force and pressure limits.

2 INJURY CRITERIA FOR POWER AND FORCE LIMITING (PFL)

The injury severity criteria under consideration by the TS 15066 working group were developed by the Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA – formally BGIA) [6]. The injury criteria are based on a literature survey establishing maximum allowable limit values on individual body regions that avoid exceeding:

1. skin/tissue penetrations that are accompanied by bloody wounds, fractures, or other skeletal damage
2. the injury severity category 1 of the Abbreviated Injury Scale (AIS1) [7]
3. injury severities with the codifications for surface injuries of the ICD-10-GM 20062 [8]

The German study shows that during collisions between a collaborative robot and a human, elastic and plastic deformations of the soft tissue component of body regions can occur. Among other medical factors, deformations are dependent on the duration of the contact. Short periods of contact create more elastic deformations of the soft tissue, and longer periods of contact produce more plastic deformations resulting in a residual three-dimensional deformation area of the soft tissue in contact with the robot component. In order to limit the degree of injury as the result of a collision, a set of medical/biomechanical limits (force and pressure) and associated soft tissue deflection properties are defined in Table 1 relative to a body model. The model establishes four main body regions and 15 individual body regions within the main regions so all anthropometric points of the body surface can be allocated force limits and tissue properties. The body model indicating the individual body regions is shown in Figure 1a.

Body model Main and individual regions with codification [a]			**Maximum allowable Limit values of the injury severity criteria (CSF, IMF, PSP) and arranging factor (CC)** [b]			
Main body regions		**Individual body regions**	**CSF [N]**	**IMF [N]**	**PSP [N/cm²]**	**CC [N/mm]**
1. Head with neck	1.1	Skull/Forehead	130	175	30	150
	1.2	Face	65	90	20	75
	1.3	Neck (sides/neck)	145	190	50	50
	1.4	Neck (front/larynx)	35	35	10	10
2. Trunk	2.1	Back/Shoulders	210	250	70	35
	2.2	Chest	140	210	45	25
	2.3	Belly	110	160	35	10
	2.4	Pelvis	180	250	75	25
	2.5	Buttocks	210	250	80	15
3. Upper extremities	3.1	Upper arm/Elbow joint	150	190	50	30
	3.2	Lower arm/Hand joint	160	220	50	40
	3.3	Hand/Finger	135	180	60	75
4. Lower extremities	4.1	Thigh/Knee	220	250	80	50
	4.2	Lower leg	140	170	45	60
	4.3	Feet/Toes/Joint	125	160	45	75
[a] BR - Body region with codification Regions - Name of the individual body region			[b] CSF - Clamping/Squeezing force IMF - Impact force PSP - Pressure/Surface pressing CC - Compression constant			

Table 1: BGIA Injury Criteria

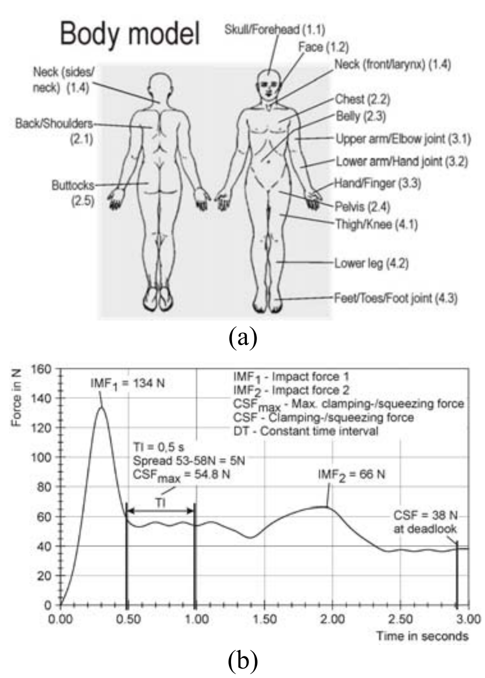

Figure 1: (a) BGIA Body Model and
(b) BGIA Force Characterization

These limits and properties are defined as follows:

1. Impact Force (IMF) – The maximum permissible force acting on a body region resulting from a robot collision where the period of contact results in an elastic deformation of the soft tissue. An impact force is defined to occur when the difference between the maximum force and other forces before and after the maximum is more than 5 N over a time interval of 0.5 s or less as depicted in Figure 1b

2. Clamping/Squeezing Force (CSF) – The maximum permissible force acting on a body region resulting from a robot collision where the period of contact results in a plastic deformation of the soft tissue. A clamping/squeezing force can be detected by a spread of the force signal of not more than 5 N over a time interval of more than 0.5 s within any time of the whole measurement as depicted in Figure 1b.

3. Pressure/Surface Pressing (PSP) – The maximum permissible partial pressure load in the case of both IMF and CSF where the contact area (CA) of the collision is small as to reduce the defined IMF and CSF limits. The critical contact area is defined as:

   In the case of an elastic deformation: CA = IMF/PSP
   In the case of a plastic deformation: CA = CSF/PSP

4. Compression Constant (CC) – is the deformation constant of a body region through which the maximum compression path is established assuming linear deformation behavior throughout the soft tissue body region.

3 PFL MEASUREMENT DEVICE

3.1 Design

Based on the proposed injury criteria and associated testing guidance provided in the BGIA report [3], NIST developed a mechanical measurement system that replicates the defined body region compression constants and measures the maximum forces applied by a robot during a collision. The following requirements were extracted from the BGIA report:

1. Devices measuring static and dynamic collision forces should be deformable along one axis and have a linear deformation behavior. The malleable components of the devices (such as linear springs) must reproduce compression constants of the individual body regions and allow loads at least up to the limit values of the forces. The linearity of the malleable components must lie within ± 5 % of the specified CC.
2. The measuring devices must have leveled, plane-parallel guided and sufficiently large collision areas in the direction of the effected collision force where the malleable measuring device components can be found between them. No permanent deformations may occur on the measuring devices as a result of the collision.
3. The force acting in a collision simulation must be measured with a suitable force measuring system in discrete time. Data must be of sufficient resolution to capture all dynamic parts of the collision force. No filtering effects may affect the measurement of the collision force, which must be determined with a maximum standard error of ± 1 % from the measured value.
4. It must be possible to verify the limit values for the pressure/surface pressing with these measuring devices. The pressure measuring sensory system may not cause a distorting damping of the impact impulse and have no influence whatsoever on the forces being measured, especially the peak forces. The pressure measuring devices must measure at least the highest partial pressure, but if possible the total pressure distribution within the colliding surface. The measuring sensory system must be able to measure the entire collision area and partial pressures with sensor areas ≤ 10 mm². Partial or peak pressure measurements must be carried out with a maximum standard error of ± 2.5 % from the measured value.

The current design of the PFL measurement device is shown in Figure 2. Based on industry feedback, the device should have a target cost of $10 000. This device measures force and displacement and supports both fixed and free space collisions along a single axis. The injury criteria compression constants are incorporated into the device through the use of ten custom compression springs with the same outer dimensions that are easily interchangeable by removing the strike plate cap. Force measurements are made using a piezoelectric force transducer which is housed between the base of the force/displacement assembly and the base support for the spring. To support performance evaluations of the device, the design also incorporates a linear variable displacement transducer (LVDT) coincident with the device axis.

A series of weights can be added to the linear slide carriage assembly during free space collisions to replicate the mass of the human body regions being struck by the robot. Also shown in Figure 2 as transparent components is the concept of incorporating future spring/damper parameters to replicate response of the human body during free body collisions. Currently there is no guidance provided for free body collisions and this is a topic of discussion within the TS 15066 working group.

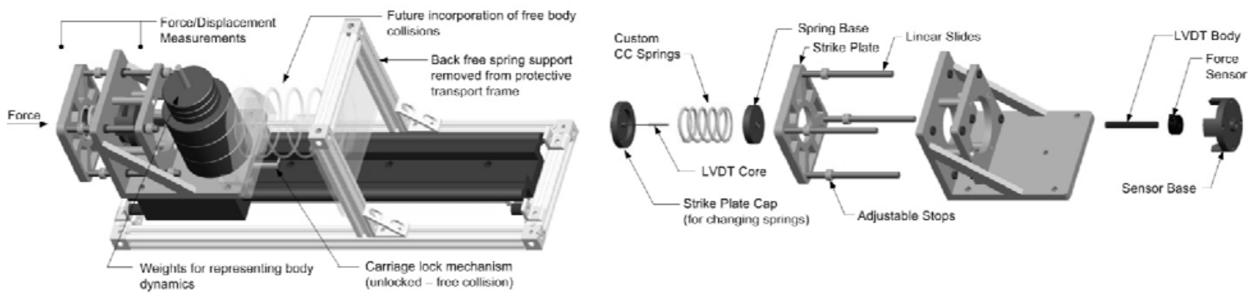

Figure 2 (left) Assembled and (right) sub-components of the NIST PFL measurement device design.

This first prototype design does not include an explicit sensor system for mapping contact pressure in order to verify the limit values for the pressure/surface pressing. After a market search of available tactile sensor pressure pads at costs ranging from \$20 000 to \$35 000, NIST is investigating alternative solutions for making these measurements in order to keep the cost of the entire measurement device close to the \$10 000 target. We are currently experimenting with a pressure sensitive paper containing microcapsules that rupture producing an instantaneous and permanent high resolution color-based topographical image of pressure variation across a contact area.

Software was developed for parameter configuration, data acquisition, and data analysis. Parameters are loaded based on the selected body region under test. The device is fixtured to a rigid surface and a robot trajectory is applied along the device axis centered on the strike plate. Data collection is triggered at the start of the impact and data is recorded for 3 seconds, based on proposed TS 15066 testing requirements. The software displays force and displacement data vs. time and graphically identifies force types and maximum force values. LVDT displacement data is also displayed and can be used to calculate forces using spring data with close correlation to the piezoelectric force transducer readings.

3. 2 Test and Evaluation

A spring manufacturer was chosen to fabricate the springs. A lot of 10 springs was produced for each of the 10 injury criteria CC values. To date, a single spring from each lot was tested in a compression testing machine to validate the nominal CC values. Initial results showed a variation in linearity during initial deflection due to uneven seating which was eliminated by regrinding the spring ends to be parallel. The actual values of spring CC constants for a single set of springs were measured following the regrinding process. Five springs met the BGIA specified tolerance of ± 5 % while three were relatively close (see Table 2). The 75 N/mm^2 and 150 N/mm^2 springs were significantly out of tolerance which may be attributed to the fact that the springs were tested to just above the maximum expected force value, which results in small deflections for these springs of approximately 3 mm and 1.5 mm, respectively. The stiffness of the springs in these regions was observed to be non-linear.

We established a calibration procedure using the free body collision weights. The device was placed in a vertical position with the carriage in a locked position. Weights were added to the impact plate to verify the force and displacement readings. Results of a calibration procedure where two 2.27 kg (5 lb) weights were placed consecutively on the strike plate are shown in Figure 3. The arrows indicate the settled force reading after the placement of each weight.

Nominal CC (N/mm^2)	Actual CC (N/mm^2)	Standard Error %
10	10.0	0.8
15	14.7	2.0
25	23.0	8.0
30	28.4	5.3
35	32.9	6.0
40	38.3	4.3
50	47.7	4.6
60	57.5	4.2
75	64.0	14.7
150	119.0	20.7

Table 2: Results of the CC validation

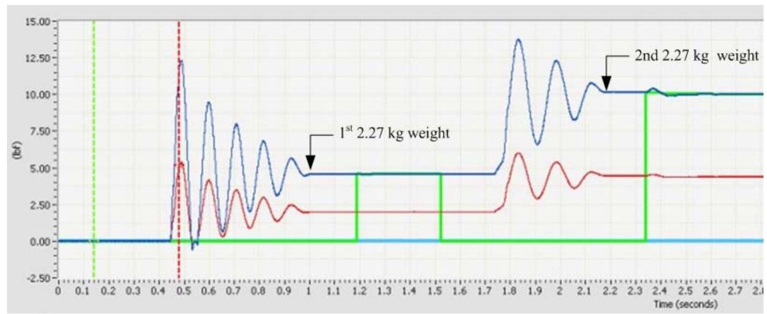

Figure 3: Calibration results for consecutive 2.26 kg (5 lb) weights

The NIST prototype PFL measurement device is shown in Figure 4. The overall performance of the device was tested using two different robots. NIST used a typical 20 kg payload industrial robot fitted with a 6-axis force transducer to perform initial testing of the device using position-based trajectories as shown in the right side of Figure 4. These tests were used to verify sensor readings from the device and included correlations between piezoelectric force transducer data, forces calculated from the LVDT displacement data and actual spring constants, and force readings from the robot force transducer. We also field tested the performance of our PFL measurement device on a prototype commercial robot.

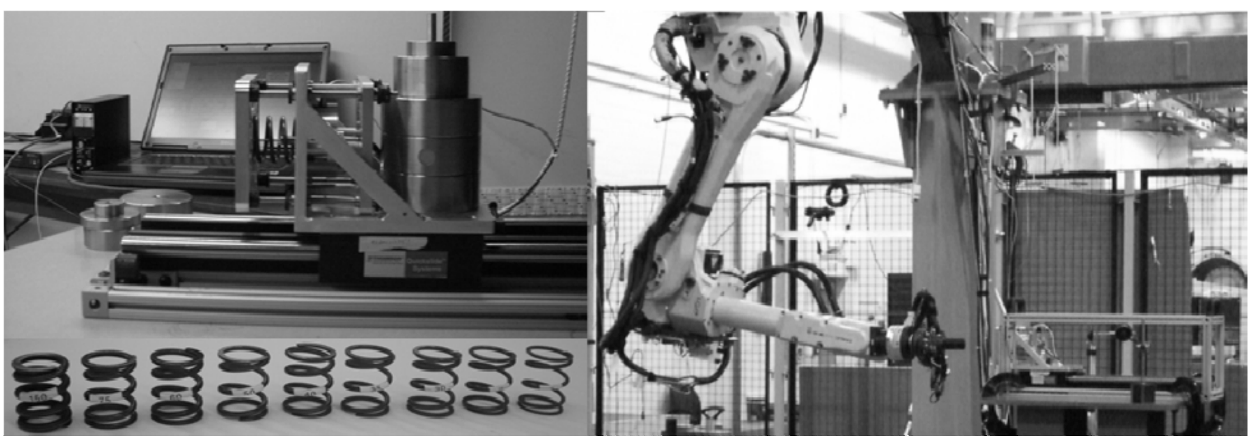

Figure 4: The NIST PFL device prototype (top-left), CC springs (bottom-left), and test set-up using an industrial robot (right)

The device performed as designed during robot impacts. We found that during testing, it was difficult to reposition and rigidly fixture the device to test different strike points along the length of a robot arm. We also identified improvements for the device software for more automated repeated captures of impact trials. Finally, we came to the understanding that rate of energy transfer varies significantly with the properties of the striking surface. A high peak impact was observed when the metallic strike plate was impacted as compared to striking the device with a conformable rubber pad over the strike plate. There is currently no requirement in TS 15066 for impact surface properties.

4 CURRENT ACTIVITIES

While the BGIA/IFA injury criteria are being used in TS 15066, work continues to develop injury criteria to ensure that maximum values chosen are not so conservative as to limit potential applications for robots operating under the Power and Force limiting mode of operation as defined in ISO 10218. NIST is collaborating with a biomechanics expert who is currently evaluating the IFA/BGIA injury severity criteria and is also investigating injury severity criteria and standardized maximum force values that resulted from studies from the transportation industry on blunt force impact injuries caused by bus and train doors. As mentioned previously, the current injury criteria do not specify parameters associated with free body collisions. NIST is working with the biomechanics expert to develop a set of spring-damper parameters to enable the NIST PFL measurement device to be configured to support free body collisions. NIST is also investigating alternative methods to measure pressure to avoid the high cost associated with pressure sensor array systems. In addition, IFA is currently working on refinements to the current injury criteria that attempt to more accurately define the soft tissue regions using two compression constants (CC1 and CC2). CC1 defines soft tissue deflections during the initial soft tissue deflection of an impact and CC2 defines the tissue properties at the bounds of its maximum deflection. IFA is also funding a pain discomfort study in an attempt to develop a minimum level of force that causes discomfort. The idea is that these reduced forces can be used to develop robot PFL collaborative applications where there are expected robot collisions with humans and forces should be limited to below injury levels. In addition to the NIST efforts, IFA and Fraunhofer IPA, also participants in the development of TS 15066, are working to develop measurement devices.

5 CONCLUSIONS

The feasibility of using springs to represent body regions of higher stiffness and small displacements needs to be investigated. Deviations in spring properties in these regions appear significant; however more analysis is needed to determine if they were induced by the manufacturing process. NIST needs to closely track modifications to the current injury severity criteria and offer input from our studies, as well as incorporate changes into future device designs.

IFA's specification of CC1 as a substrate on the strike plate shows promise to better replicate the properties of soft tissue regions and provides a basis for a standardized strike plate substrate material. The TS 15066 working group must develop more detailed test device requirements and associated test methods to ensure that the results of performance tests for robots with PFL functionality are not device dependent. Finally, a standard method of device calibration is needed to validate these PFL measurement devices.

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