Being safe around collaborative and versatile robots in shared spaces

Protocol

Test Robot Arm for Collision with a Movable Object
(measurement of peak pressure)

ROB-LIE-3

The specific purpose of this protocol is to validate the safety skill "limit interaction energy" by measurement. Its scope is limited to robot arms operating in the domain Manufacturing. In this context, the skill "limit interaction energy" is often used to protect workers from injuries caused by robot collisions where the robot hits a part of the human body that can freely move. The validation of this protocol requires that the reader has a bio-fidel force and pressure measurement device available. The instrument must allow for measuring the highest pressure during the collision.

Readiness Level	Description
8	Protocol was tested and reviewed by multiple external parties.

COVR is a community effort and values any honest feedback to our services. Please feel free to express your opinion about this protocol. The feedback form is only one click away. Thanks for making COVR even better!

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CONTENTS

1 Introduction

The purpose of this protocol is to validate through measurements whether the contact force and pressure that the robot applies to the human robot during physical contact do not exceed the applicable biomechanical limit values (e.g., those of ISO/TS 15066). This protocol is specifically intended for validating impacts, in which the robot does not clamp one or more body parts of the human operator, since they are spatially unconstrained and can move freely (no obstacles). The testing procedure described below involves a bio-fidel instrument that the user must mount on a stiff frame (no freely moving masses).

Example: A lightweight robot executes a pick and place task next to the human operator. A typical case of foreseeable misuse is when the operator spontaneously reaches into the robot workspace, for instance to correct the position of a slipped component. In such a situation, the robot is likely to collide with the outstretched arm of the human. Since there are no physical constraints, the arm can move freely into the direction of the moving robot. The physical contact between robot and human will most likely last only for a short duration (below 0.5 s), why it is classified as transient.

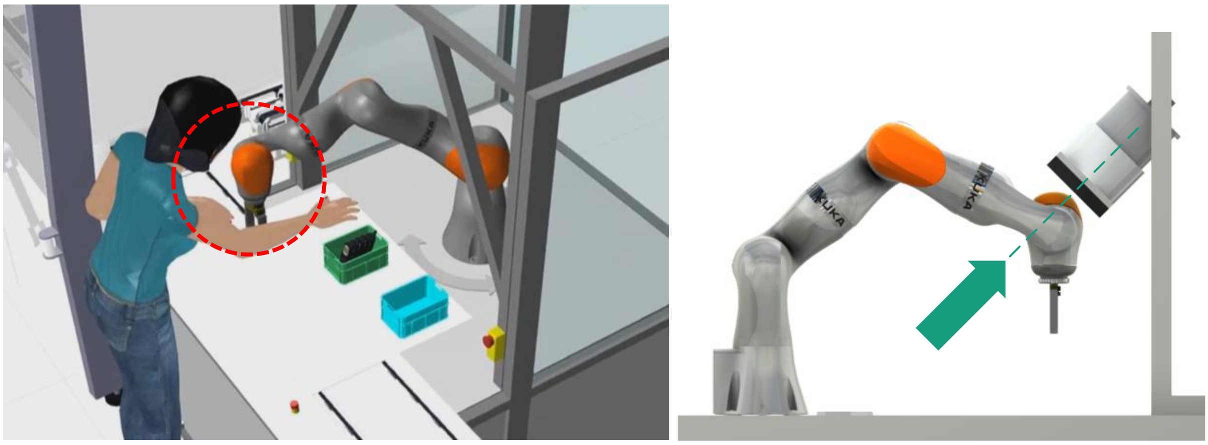

Figure 1: Exemplary situation of an impact (left) and the principle test setup to analyze such contacts (right)

1.1 Scope and limitation

This protocol is specifically limited to the following profile:

Skill	limit physical interaction energy
System	robot arm
Sub-System	n/a (no subsystem)
Domain	cross-domain
Conditions	environment: indoor-factory obstacle (human body part): moving (not fixed)
Measurement Device(s)	device that mimics the biomechanical behavior (bio-fidelity) of the human body (at least of its considered part) and that can measure force and pressure

	Warning
⚠	This protocol supports users only to validate the effectiveness of the skill listed in the profile above. The skill should be a technical measure for the robot system to mitigate the risk of one potentially hazardous situation as identified in the mandatory risk assessment. Consequently, the risk assessment must be done before using this protocol.

1.2 Definitions and Terms

Industrial robot (source: EN ISO 10218-1)

Automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications

Industrial robotic system (source: EN ISO 10218-1)

System comprising:

- Industrial robot
- End effector(s)
- any machinery, equipment, devices, external auxiliary axes or sensors supporting the robot performing its task

Collaborative operation (source: EN ISO/TS 15066)

State in which a purposely designed robot system and an operator work within a collaborative workspace.

Collaborative robot (source: EN ISO 10218-2)

A robot designed for direct interaction with a human within a defined collaborative workspace.

Collaborative workspace (source: ISO/TS 15066)

Space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation.

System integrator

Company or person who created the collaborative robot and brought it into productive operation. The system integrator is responsible for doing the risk assessment and must ship the collaborative robot with an instruction manual, which refers to the residual risks of the robot system.

Robot operator

A person who is working with or beside the robot within the collaborative workspace.

Unintended contact

Contact refers to a state in which the robot and human are in touch and applying mechanical forces to each other. A contact is considered as unintended if the robot touches the human accidentally due to failure or misuse.

Transient contact (source: ISO/TS 15066)

Contact between an operator and part of a robot system, where the operator body part is not clamped and can recoil or retract from the moving part of the robot system. In the course of the contact force recorded over time, the transient contact phase is the part of the signal that ranges from initial contact to 500 ms thereafter.

Quasi-static contact (source: ISO/TS 15066)

Contact between an operator and part of a robot system, where the operator body part can be clamped between a moving part of a robot system and another fixed or moving part of the robot system. In the course of the contact force recorded over time, the quasi-static contact phase begins 500 ms after initial contact.

Application (source: EN ISO 10218-2)

Intended use of the robot system, for instance, the process, the task and the intended purpose of the robot system (for instance, spot welding, painting, assembly, palletizing).

Measurement instrument

Bio-fidel instrument to measure the contact forces and pressures on a collaborative robot system for identified cases of unintended and potentially hazardous contacts.

2 Concept and Objectives

The concept of the validation process is to provoke an impact with a real robot system and measurement instrument that emulates the biomechanical response of the human body. During the test, the robot must operate under the same conditions, as it will in its real application. The objective of the test is to prove whether the applied safety skill “limit physical interaction energy” prevents the robot from exceeding the applicable biomechanical limit values. Additional means to reduce the contact forces and pressures, which are not safety-rated, must be deactivated during the tests.

2.1 Hazardous Situations

Here, the term *hazardous situation* refers to an *impact* between robot and one or more body parts of the human operator as introduced in Section 1.1. The protocol user must follow the procedure specified by this document for every impact identified in the risk assessment as a case of foreseeable and potentially hazardous misuse.

	Suggestion
	The intended use and foreseeable misuse of the robot, as clarified in the risk assessment, can help to identify potentially hazardous impacts to be tested. Typically, losing consciousness or malicious mischief/vandalism is no foreseeable misuse.

2.2 Target Behavior and Metrics of the Safety Skill

The target behavior of the skill “limit physical interaction energy” is to prevent the robot from exceeding the biomechanical limit values referenced in the risk assessment.

The target metrics for the test base on the following physical and measurable quantities, which represent a threshold that the output values of the test must not exceed to pass the test successfully. For validating the robot skill “limit physical interaction energy,” the output values are:

- Maximum collision force F_{TR} for transient contact phase
- Maximum collision pressure p_{TR} (normal stress) for transient contact phase

The risk assessment should specify the target metrics (maximum allowable values). For this validation protocol, the target metrics are the following limits of the output values:

- Force limit $\hat{F}_{TR}$ for transient contact (maximum allowable impact force)
- Pressure limit $\hat{p}_{TR}$ for transient contact (maximum allowable normal impact stress)

The target metric can vary for different parts of the human body, so it is essential to ensure which metric value applies to which body part. Please report the values of the target metric for each test using the form in Annex B.

Example: Endangered Body Part and Limit Values

Body Part	**Force (N)**	**Pressure (N/cm²)**	**Stiffness (N/mm)**
Forearm muscle	320	360	40
Source	ISO/TS 15066:2016		

3 Conditions

3.1 System

The term *system* refers to the collaborative robot system consisting of:

- Type of arm
- Type of tool
- Type of workpiece

The protocol user must consider all changing parts of the system as different system-related conditions. For instance, if the robot picks up a workpiece, the system conditions change the moment the gripper is connected to the workpiece.

Note: For specific applications, it is possible that the robot works with different tools and workpieces, while the robot's movement and proximity to the human does not change. One specific hazardous situation can, therefore, apply to various conditions. Refer to the risk assessment to find out which task-related conditions can change. In case the robot works with more than one tools and / or workpiece, validate the capabilities of the safety skill for all existing system configurations per hazardous situation. Each configuration extends the number of tests since each test can only examine one system configuration in one hazardous situation.

Please report the system composition for every single test using the form in Annex B.

Example: System Configuration

Robot Arm	
Manufacturer	The Robot Company
Model	cobot 10
Serial Number	cobot 10
System Configuration	Pneumatic Package Safety Package
Control Software	coControl, version 2.3.1
Robot Tool	
Manufacturer	The Tool Company
Model	cotool 5
Description	Magnetic gripper
Work Piece	
Manufacturer	My Company
Model / Type	Screw M12
Description	20 cm long

When the safety skill responds to the contact, its configuration is likely to affect the robot behavior. Therefore, it is also necessary to record the configuration of the safety skill applied. Since the robot manufacturers implement their safety functions differently, it could be necessary to use a customized list to record the selected safety functions and their parameters applied. The following example shows how a customized recording can look like.

Example: Applied safety configuration with direct impact on the safety skill

Safety Skill Properties	
Force Limit	100 N
Velocity Limit	0.5 m/s
Torque Limit Axis 1	160 Nm

In the event the robot program under test switches between different sets of safety configurations, it is necessary to execute separate test for every safety configuration.

Except the safety configuration, the state, the robot has when the impact occurs, has also a significant influence on the output values of the test. The relevant states are:

- Joint configuration (axes position)
- Direction and magnitude of TCP velocity (depends on the axes velocities)

For a proper validation test, it is necessary to establish the same robot state as the robot would have in case of an impact. Therefore, the point of interest for the test is the point of the robot path at which an impact is most likely. The risk assessment should give details about the exact moment and position of this point. Therefore, the risk assessment is the primary source to determine the robot state for the test.

Every point along the robot path corresponds to a specific tool position. The robot's movement along the path implicates a tool velocity. The robot kinematics create a relation between the position of the robot axes (joint space) and each point on the path (workspace), so that the axes' positions relate to a specific tool position. Over the teach-pendant of the robot, it is possible to determine the current axes position and the velocity of the tool or the TCP (tool center point) from the robot program. Please report both for every single test using the form in Annex B.

Example: System State

Configuration Space	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
Axes Position (deg)	11,9	0	0	0	0	0	
Axes Velocities (deg/s)	60	30	-60	30	0	0	
Workspace	**ABS**	**X**	**Y**	**Z**			
TCP Velocity (mm/s)	750	0	750	0			
Override (%)	100						

The user must derive appropriate test points along the robot paths from their risk assessment.

This protocol does not consider a robot manipulator with a sub-system (mobile platform, etc.). If the system under test has a sub-system, please check the COVR toolkit for a protocol that deals with the sub-system in question.

3.2 Environment

The protocol user must consider the following environmental conditions for the validation tests:

- No obstacles (endangered part of the human body is spatially unconstrained and can move freely)

3.3 Miscellaneous

Other relevant conditions are:

- Location of the contact area on the robot structure (incl. tool or workpiece; according to the risk assessment)
- Endangered body parts (parts of the human body the robot can affect; see Section 2.2)

Use the form of Annex B to record the location and shape of the contact area on the robot structure.

Example: Misc. Conditions

Contact Area (on robot structure)	
Location	Workpiece (screw M12), lower side of the screw thread (face side of a cylinder)
Photo	(insert a photo here)

Report the endangered body parts next to theirs associated limit values. Add to each body part its stiffness parameter and the source of the limit values (see example in Section 2.2). Annex A summarizes some stiffness parameters of the human body.

4 Test Setup

4.1 Equipment

The following sensors are required to perform the test:

- Load-cell for force measurement over time
- Foil sensor for peak pressure measurement

The load-cell must be part of an instrument that mimics the biomechanical characteristics of the human body or at least of the endangered body parts. **Fehler! Verweisquelle konnte nicht gefunden werden.** depicts the general design of such a device. It consists of an impactor attached to a changeable spring. Linear guides ensure that the impactor can move only into the active direction of the spring. The spring is further attached to the load-cell which is rigidly connected to the housing of the instrument. A soft damping material covers the top side of the impactor. The combination of damping material and spring must realize the same biomechanical characteristics the considered part of the human body has. The foil sensor for pressure measurement is on the top of the damping material.

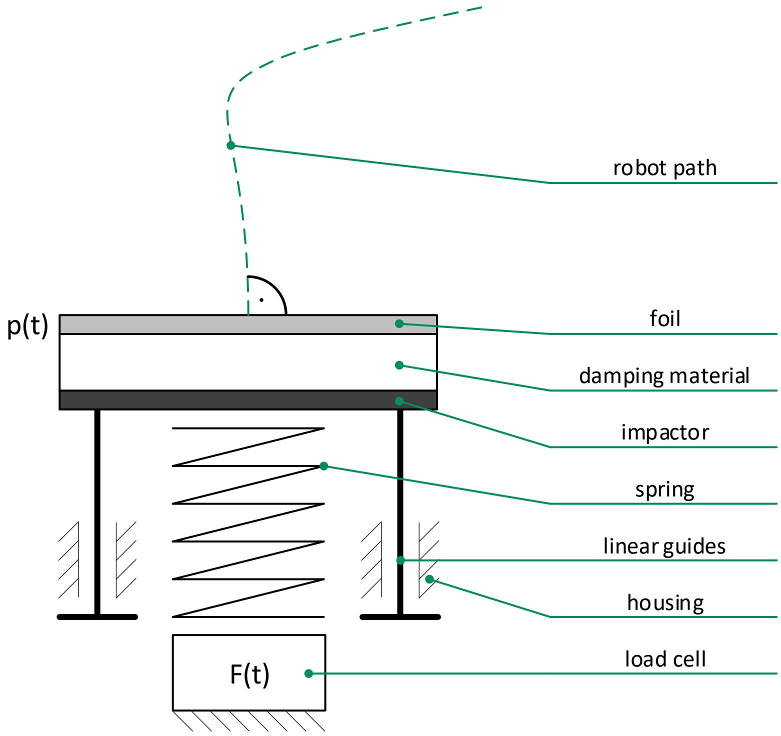

Figure 2. General design of the measurement instrument

The load-cell for force measurement must fulfill the following requirements:

	Minimum	Recommended
Number of axes	1	1
Calibrated range	(overall max. limit value)	(3x overall max. limit value)
Relative error (linearity)	<2%	<0.5%

Table 1. Requirements for load cell (sensor for measuring the contact force)

The foil sensor for measuring the contact pressure (normal stress within the contact area) must allow for peak measurement (highest pressure during contact). The material of the sensor must be flexible to withstand the deformations of the damping material lying below. Moreover, the foil sensor must fulfill the following requirements:

	Minimum	Recommended
Calibrated range	(overall max. pressure limit)	(3x overall max. pressure limit)
Relative error	<10%	<10%

Table 2. Requirements for foil sensor (sensor for measuring the pressure within the contact area)

Note 1: Some foil sensors are available with different measurement sensitivities. Use always the highest possible sensitivity so that the result is still within the measurement range. The sensitivity is too high if the signal of at least one measurement cell of the foil remains at the upper range value.

Note 2: Use only foils with a sensitive area that covers at least 30% and less than 90% of the expected contact area.

Use the form in Annex B to report the capabilities of both sensors used for the validation.

Example: Sensors

Feature	**Force Sensor**	**Pressure Sensor**
Manufacturer and Type	Sensor Company, PE 1000	Sensor Company, Foil 250
Calibrated Range	1000 N	250 N/cm^2
Relative Error (linearity)	<0.25%	<10%
Miscellaneous	Number of axes: 1	Temperature: 21°C Relative Humidity: 60%

4.2 Method

The following devices must be available for data acquisition:

- A computer for controlling the measurement instruments
- All devices and software (running on the computer) necessary to control the sensors and to record their signals (incl. data logger, charge amplifier, etc.)

Note: Manufacturers of commercially available measurement systems usually provide software to control their devices and to analyze the results. If such a system is used, ensure that you have access to the associated software. It can be the case that there are separate tools for force and pressure measurement, which must be run in parallel.

Acquisition the force signal must comply with the following requirements:

	Minimum	Recommended
Sampling Frequency	1’000 Hz	10’000 Hz
ADC Resolution	12 bit	16 bit

Table 3. Requirements for data acquisition

Note: Ensure that the force sensor has a sufficient bandwidth that allows for sampling the signal at the specified sampling frequency.

Please record the applied configuration using the form in Annex B.

Example: Acquisition Configuration

Feature	**Force Sensor**	**Pressure Sensor**
Sampling frequency	10.000 Hz	
ADC resolution	16 bit	
Recording Software	Force Measurement Program	

5 Procedure

5.1 Test Plan

The test plan summarizes all situations which the risk assessment has identified as hazardous contacts between robot and one or more body parts of the human operator, incl. all combinations of applicable conditions (system configurations, etc.). It, therefore, provides a detailed overview of which tests are necessary to validate the safety skill.

The protocol user must test each impact as recorded in the risk assessment (see Section 2.1), which means to provoke an impact between the robot and a proper measuring instrument (see Section 4.1 and **Fehler! Verweisquelle konnte nicht gefunden werden.**). The purpose of the test is to prove whether the robot exceeds the metrics or not (see Section 2.2).

According to Chapter 3, the protocol must consider the following conditions:

- Robot system
  - Type of arm
  - Type of tool
  - Type of workpiece
  - Joint configuration
  - Direction and magnitude of TCP velocity
- Environment
  - No obstacles
- Miscellaneous
  - Location and shape of the contact area on the robot structure
  - Endangered body parts

For the validation of the safety skill, it is necessary to measure all possible combinations of conditions that apply to the considered hazardous situation. It is, therefore, recommended to prepare a list that organizes all hazardous situations and applicable conditions row-wise. Each row represents a particular test case. To reduce the number of single tests, it is recommended to focus on the validation test related to the most dangerous and most likely contact situations. The protocol user must run and report each selected test using the form in Annex B. It is recommended to note a short rationale for all unselected tests. The protocol user should execute a test measurement to check whether everything is working properly. If the test measurement went well, the actual test must be executed three times to cope variability.

5.2 Preparation

5.2.1 Test Arrangement

The preparation of the test arrangement includes to set up all devices that are required to validate the robot system. Please go through the following to prepare the tests properly:

Measurement Equipment

- Connect all sensors to their loggers and the loggers to the computer for controlling the measurement.
- Configure the parameters of the data acquisition within the range specified in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**.
- Ensure that the acquisition of all signals works properly as configured.

Measurement Instrument

- Install the spring and apply the damping material to the impactor (see test plan). Make sure that the characteristics of the used combination match the stiffness of the endangered body part (see Section 3.3).
- Attach the measurement instrument to a mechanically stiff support that holds it in place during the test. The contact forces applied to the measurement instrument should not significantly move or deform the support (e.g., use profiles made of aluminum).
- Orient the measurement instrument perpendicular to the moving direction of the contact point on the robot surface before initial contact with the measurement instrument (Figure 3).

Pressure Sensor

- To avoid damage to the pressure foil, cover it with a PTFE foil (thickness below 50 µm; only for peak / passively measuring pressure foils).
- Rough surfaces can result in small regions of significant peak pressures. To avoid them, use a microfiber cloth (thickness below 500 µm; only for peak / passively measuring pressure foils).
- Make sure that the sensitive area of the foil covers the contact area completely.
- If necessary, use rubber bands to attach the foil to the impactor of the measurement instrument. Ensure that the rubber band does not run over the sensitive area of the pressure foil.

⚠	**Warning**
	The applied combination of spring and damping material must emulate the response behavior of the body part to be tested. In order to select the right combination, it may also be necessary to consider the shape of the contact area on the robot surface.

⚠	**Warning**
	The stiffness of the instrument support must be 20x higher than the stiffest spring used in the tests.

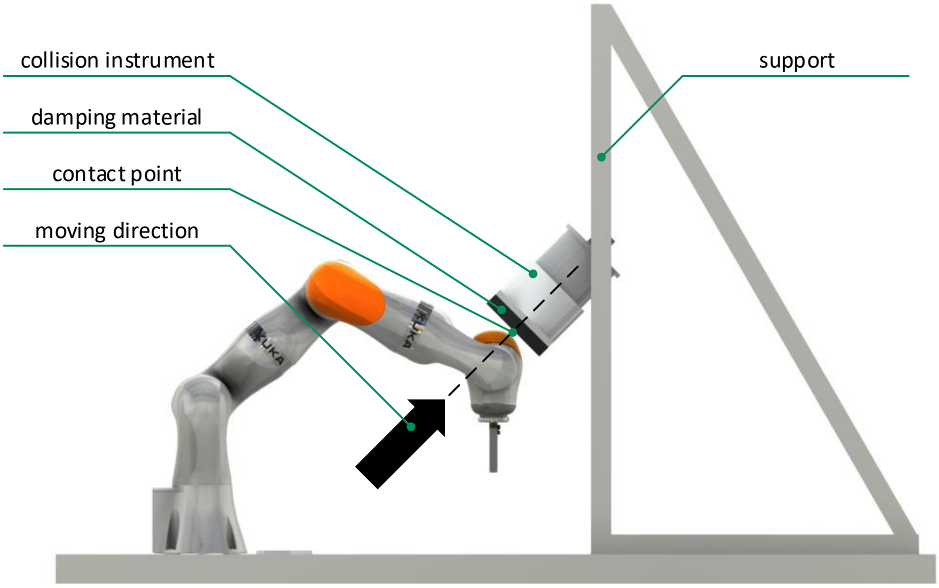

Figure 3. Schematic drawing of the setup

Use the form in Annex B to record the applied spring and damping material (*SH = shore hardness):

Example: Configuration of the Measurement Instrument

Spring Rate (N/mm)	120
Hardness of Pad (SH*)	40
Thickness of Pad	30 mm

*) Shore Hardness

5.2.2 System Conditions

The protocol user must configure the robot in the exact way as it will run later in the application, which includes at least the following steps:

- Switch the robot on one hour before beginning the tests (warm-up phase).
- Install all tools and provide all workpieces the robot will use or handle later in the application.
- Install the final program that involves all movements and actions that the robot will perform later in the application.
- Configure all available safety-functions.
- Deactivate all additional safety measures that are not safety-rated.

⚠	**Warning**
	The safety configuration, and so the safety skill, is often a part of the robot program or inseparably connected with it. Therefore, the protocol user must not change the robot program after passing the validation successfully. It is highly recommended to store a backup of the successfully validated program and to lock the robot control unit so that only authorized people can modify the program or the safety configuration. Any modification to the program requires a new validation of the safety skill.

Note: If the robot has no safety functions to limit the interaction energy, the protocol user must test the worst case scenario, which is the robot moves at maximum velocity, even if not required for the application.

5.2.3 Environmental Conditions

There are no environmental conditions that the protocol user must explicitly establish for the test. It is, however, highly recommended to run the tests in the same environment in which the robot system will operate later.

In some cases, the software for signal analysis requires environmental data (e.g., temperature and humidity) to compensate for measurement errors. Check the sensors' manuals for information about environmental data that must be noted. Especially foils for peak-pressure measurement are sensitive to humidity and temperature.

5.3 Test Execution

Apply the following steps for each test case:

- Move the robot slowly to the point where the impact can occur (see test plan or risk assessment).
- Install the measurement instrument at the contact point. Check if the instrument is in the right position and orientation. The position is correct when the robot almost touches it when reaching the contact point on the robot surface. The orientation is right when the contact point moves perpendicular to the impactor plate of the measurement instrument (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**) before initial contact.
- Move the robot backwards along the programmed path. Choose a proper starting position from which the robot has enough time to accelerate to its programmed velocity before reaching the contact point.
- Take a photo of the test situation (recommended). Place a reference number (e.g., written on a piece of paper) in the picture to ensure that the picture can clearly be assigned to the measurement data later.
- Start the measurement systems.
- Start the robot movement.
- After the robot hit the measurement instrument and stopped, take another photo of the situation (recommended).
- Save the recorded signals.
- If the robot is still in contact with the measurement instrument, release it by moving it slowly under manual control.
- Take the pressure foil from the impactor and install a fresh one.
- Rearrange the position of the pad if it slipped because of the contact force.
- Repeat the tests twice (see Section 5.1).

Note: In the event the area around the contact point is confined and does not allow installing the measurement instrument properly, try to find a different point along the path at which the robot has a comparable velocity and joint configuration. If the workaround is not possible, reduce the robot's velocity so that the human can easily avoid the contact.

5.4 Data Analysis

After finishing the last repeat, there should be three results from three tests available. It is necessary to filter each signal before processing them further. Since the result achquired by the pressure foil is technically a single image, it can be necessary to apply an additional image filter that reduces the noise across all pixels. The requirements for both filter types are:

Signal Filter (for force only)	Minimum	Recommended
Signal filter type	1st order Butterworth low pass	4th order Butterworth low pass, zero-phase
Cut-off frequency	200 Hz	200 Hz
Image Filter (for pressure only)	**Minimum**	**Recommended**
Image filter type	Average filter	Gaussian filter
Standard deviation	N/A	$\sqrt{2/\pi}$

Table 4. Requirements for signal and image filtering

For compensating image noise, it is highly recommended to use a software that has such filters included. The manufacturers of the pressure measurement system usually provide such tools for their sensors. Use the form in Annex B to record the applied filter configuration.

Example: Signal Filter Configuration

	Force Sensor	Pressure Sensor
Signal Filter Type	4th order Butterworth low pass, zero-phase	
Cut-off Frequency	200 Hz	
Image Filter Type		Gaussian filter
Standard Deviation		$\sqrt{2/\pi}$

After filtering, the offset can be compensated by calculating the average signal value from 0.5 s to 1.5 s (0 s marks start of signal recording, not initial contact) and subtracting it from all signal values. Figure 4 illustrates the procedure for the force signal. When using a measurement instrument that includes a software for data recording and analysis, make sure that the manufacturer has implemented offset compensation.

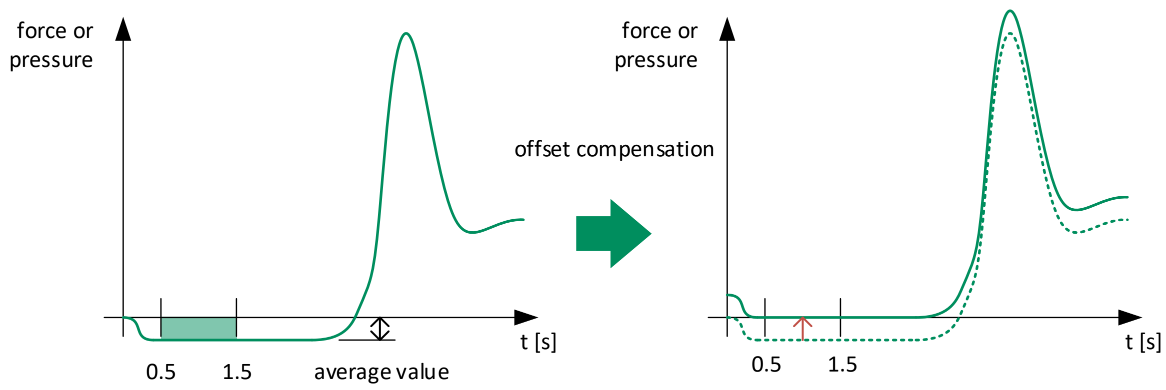

Figure 4. Procedure for offset compensation

The nature of an impact under unconstrained spatial condition is that the affected body part can move freely. However, the proper use of the measurement instrument requires to attach it to a solid support frame. Such a setup cannot simulate the energy transfer that occurs during an impact as the support frame holds the measurement device rigidly in place. This makes it, therefore, necessary to convert the maximum forces and pressures to the case where the instrument can move as freely as the body part.

After all signals were processed, determine the maximum force and pressure value. Make sure that the maximum values lie within the time window from 0 to 0.5 s (0 s marks initial contact; see Figure 5). Next, determine the time T at which the maximum force appears. Use the maximum force F_{TR} and the time T to determine the desired reduction factor R

$$R = \sqrt{\frac{m_H}{m_H + \frac{2}{\pi}\frac{T}{v_R}F_{TR}}} \quad .$$

The variable m_H is the effective mass of the human body. If this mass is unknown, please take the correct value from Table 5. The variable v_R denotes the velocity, the robot had when it hit the measurement instrument. If v_R is unknown, use the velocity limit as specified in the safety configuration. In case the robot has no safety-rated velocity limitation, use the maximum possible velocity the robot can reach.

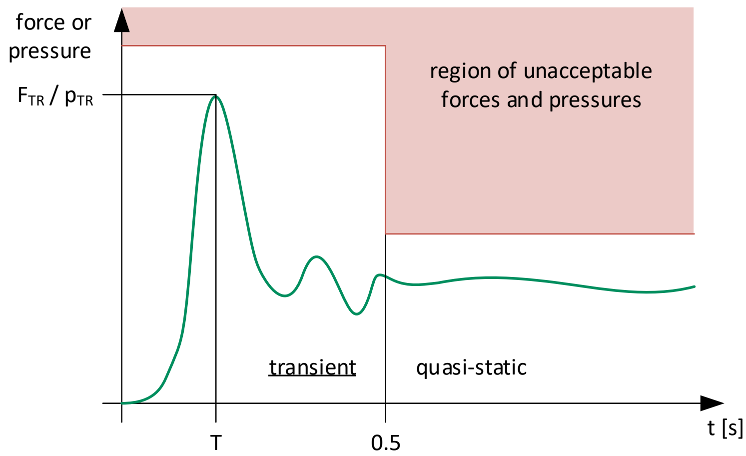

Figure 5. Representation of acceptable forces and pressures

Once the reduction factor R is calculated, round it to the first digit after the comma and multiply it to the maximum force F_{TR} and maximum pressure p_{TR} measured in the collision test. When calculating R, ensure that all values have SI units (mass in [kg], force in [N], time in [s], and velocity in [m/s]). The reduction factor R is always lower than one $R < 1$ and will, therefore, reduce the maximum forces and pressure to values which the measurement instrument would have recorded if it was not attached to a stiff frame and if its total mass were equal to m_H.

Affected Body Parts	m_H **(kg)**
Head	10
Neck, trunk, upper extremity (upper and lower arm)	50
Hand	5
Lower extremities	90

Table 5. Effective masses of human body parts

Record the maximum force and pressure value measured, the time to the maximum force, the calculated reduction factor, and all parameters that the reduction factor R includes. Use the form available in Annex B.

	Suggestion
	To minimize the efforts for the pressure measurement, it is recommended to perform only a force measurement first. If the maximum contact force converted with R is significantly below the applicable limit value, repeat the test three times including pressure measurement. If the maximum force from the first test already exceeds the force limit, the protocol user can forego pressure measurement for this test at all.

Example: Result from Data Analysis

Reduction factor to convert measurement values				
Effective Human Mass (kg)	50	50	50	
Maximum Force* (N)	313	301	330	
Time to Maximum* (s)	0.23	0.21	0.24	
Robot Velocity* (m/s)	0.5	0.5	0.5	
Effective Robot Mass (kg)	92	81	101	
Reduction Factor	0.59	0.62	0.58	
*) only required if the effective robot mass is unknown				
Measured maximum values	**Test 1**	**Test 2**	**Test 3**	**MAX**
Maximum Force (N)	313	301	330	330
Maximum Pressure (N/cm^2)	54	59	61	61
Reduced Force (N)	185	187	191	191
Reduced Pressure (N/cm^2)	32	37	35	37

If the highest maximum of all reduced force and pressure values exceeds the applicable limit value, the safety skill fails the test. Otherwise, it successfully passes the test. When the test fails, it is recommended to modify the robot program (e.g., reducing the velocity) and to start over the validation process. Other options could be a modification of the safety configuration or conditions.

5.5 Report

Use the form in Annex B to report all conditions and results of the tests. After finishing the validation successfully (all tests passed), add the filled forms to the documentation of the risk assessment. They serve as proof that the applied safety skill works properly and provides the expected protection to the robot operator. Use the last section in the form to record the overall test result (passed/failed).

Example: Summary

	Test 1	**Test 2**	**Test 3**	**ALL**
Test Passed	yes	yes	yes	yes

A Stiffness Parameter of the Human Body

See Table 6 to pick the right combination of damping material and spring to mimic the biomechanical characteristics of various body regions.

Note 1: You can neglect Table 6 if you have other and also reliable data for configuring the spring-damping characteristics of the measurement instrument. However, record the source of your data in the report forms.

Note 2: Data given in Table 6 are subject to modifications.

Table 6. Combinations of damping material and spring to mimic the biomechanical characteristics for various body regions (source: DGUV FBHM 080)

Body region	Hardness (shore A)	Thickness (mm)	Spring (N/mm)
Skull and Forehead	70	7	150
Face			75
Hand and Finger			75
Neck			50
Forearm and Wrist			40
Chest			25
Pelvis			25
Lower Leg	30	14	60
Upper Leg and Knee			50
Back and Shoulder			35
Upper Arm and Elbow			30
Belly	10	21	10

B Report Form

Use the form on the next page to record the data for each test.

COVER
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Test ID / Test no	
Hazard ID	
Description	
Photo	

Setup

Sensors

Feature	**Force Sensor**	**Pressure Sensor**
Manufacturer and Type		
Calibrated Range		
Relative Error (linearity)		
Miscellaneous		

Acquisition Configuration

Feature	**Force Sensor**	**Pressure Sensor**
Sampling Frequency		
ADC Resolution		
Recording Software		

System Configuration

Robot Arm	
Manufacturer	
Model	
Serial Number	
System Configuration	
Control Software	
Robot Tool	
Manufacturer	
Model	
Description	
Work Piece	
Manufacturer	
Model / Type	
Description	

Safety Skill Properties (can be test-specific)

Test Specifics

System State

Configuration Space	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
Axes Position (deg)							
Axes Velocities (deg/s)							
Workspace	**ABS**	**X**	**Y**	**Z**			
TCP Velocity (mm/s)							
Override (%)							

Misc. Conditions

Contact Area (on robot structure)	
Location	
Photo	

Endangered Body Part and Limit Values

Body Part	**Force (N)**	**Pressure (N/cm^2)**	**Stiffness (N/mm)**
Source			

Configuration of the Measurement Instrument

Spring Rate (N/mm)	
Hardness of Pad (SH*)	
Thickness of Pad	

Test Result

Signal Filter Configuration

	Force Sensor	Pressure Sensor
Signal Filter Type		
Cut-off Frequency		
Image Filter Type		
Standard Deviation		

Result from Data Analysis

Reduction factor to convert measurement value				
Effective Human Mass (kg)				
Maximum Force* (N)				
Time to Maximum* (s)				
Robot Velocity* (m/s)				
Effective Robot Mass (kg)				
Reduction Factor				

*) only required if the effective robot mass is unknown

Measured maximum values	Test 1	Test 2	Test 3	MAX
Maximum Force (N)				
Maximum Pressure (N/cm^2)				
Reduced Force (N)				
Reduced Pressure (N/cm^2)				

Summary

	Test 1	Test 2	Test 3	ALL
Test Passed	yes	yes	yes	yes