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Robotics — Collaborative applications — Test methods for measuring forces and pressures in human-robot contacts

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Contents

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 299, *Robotics*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

All testing methods specified in this document represent the latest state-of-the-art in the research field of contact measurement and testing with robots made for biomechanically safe interactions with humans. The procedures described in this document have been developed with a focus on practical applicability and several examples have been included in the annexes to this effect. The intended users of the document include integrators, operators, and users of collaborative applications as well as manufacturers of pressure-force measurement devices (PFMD).

The purpose of this document is to facilitate the application of other standards such as ISO 10218-2:—[1], Annex N, robot applications and robot cells integration (based on RIA TR R15.806:2018) or ISO/TS 15066.

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1) Under preparation. Stage at the time of publication: ISO/FDIS 10218-2:2023.

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Robotics — Collaborative applications — Test methods for measuring forces and pressures in human-robot contacts

1 Scope

This document specifies methods of measuring forces and pressures in physical human-robot contacts. It also specifies methods for analyzing the measured forces and pressures. It further specifies the characteristics of pressure-force measurement devices (PFMD).

This document applies to collaborative applications deployed in an industrial or service environment for professional use.

This document does not apply to non-professional robots (i.e. consumer robots) or medical robots, although the measurement methods presented can be applied in these areas, if deemed appropriate. Additionally, this document does not apply to organizational aspects for performing contact measurements (e.g. responsibilities or data management), assessment of other mechanical contact types (e.g. friction or shearing), assessment of other contact-related hazards (e.g. falling, electrical or chemical hazards). Further, this document does not set requirements for specific PFMD-design or specify methods to identify contact hazards.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10218-2[2], *Robotics — Safety requirements — Part 2: Industrial robot systems, robot applications and robot cells*

ISO 12100, *Safety of machinery — General principles for design — Risk assessment and risk reduction*

ISO/IEC Guide 50, *Safety aspects — Guidelines for child safety in standards and other specifications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12100 and ISO 10218-2 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
contact hazard
intended or unintended physical contact between human and robot or robot system in which the robot or robot system exerts forces and pressures on the human body

3.2
pressure-force measurement device
PFMD
measuring instrument with sensors to record forces and pressures of mechanical contacts

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2) Under preparation. Stage at the time of publication: ISO/FDIS 10218-2:2023.

3.3
biomechanical response
behaviour of a biological system when subjected to mechanical load that can be described by *biomechanical response curves* (3.4)

3.4
biomechanical response curve
curves that plot the contact force as a function of tissue deformation

4 Overview

4.1 General

The test methods presented in this document provide evidence through measurement whether a robot or robot system (hereinafter referred to as robot for simplicity) deployed in a collaborative application (hereinafter referred to as application for simplicity) complies with applicable force and pressure limits during physical contact with humans. Physical contact can result either from intended use or reasonably foreseeable misuse of the robot under test.

The testing procedure typically comprises several measurements of contact hazards (as identified by the risk assessment) that are replicated with the robot deployed in the target application environment. In such tests the forces and pressures, that the robot can exert on humans during physical contact, are measured. The robot passes the tests if the contact forces and pressures measured in the relevant contact situations do not exceed the applicable biomechanical limits.

If the applicable biomechanical limits also apply to children, the measurement procedures given in this document shall be executed in accordance with ISO/IEC Guide 50.

A pressure-force measurement device (PFMD) is used to measure forces and pressures, but also to replicate the biomechanical response of the human body. For replicating the biomechanical response, a PFMD can comprise various viscous and elastic materials.

The following list summarizes the steps of a proper test:

a)   Preparation of the robot and the test conditions;

b)   Replicating the contact situation by letting the robot under test collide with the PFMD;

c)   Analyzing the forces and pressures measured;

d)   Comparing the measurement values to the applicable biomechanical limits (if the measurement values do not exceed the biomechanical limits, the robot passes the test for the target application environment; otherwise, it does not pass the test);

e)   Documentation of the test results;

f)   If the robot does not pass the test for the target application environment, it will be possible to reduce force and/or pressure by modifying the robot. Repeat all the steps from a) to e) if the robot is modified and document the new test conditions.

4.2 Contact types

Human-robot contact situations can be categorized into intended or unintended contacts. Intended human-robot contacts are typically interactions between human and robot to complete a common task. Unintended human-robot contacts typically result from reasonably foreseeable misuse. Both contact categories shall be assessed through measurement if identified as relevant by the risk assessment. From here on, both contact categories will be referred to as *contact hazard*.

Any contact hazard can be classified by the following independent key contact characteristics:

a) Load profile – describes the course of the contact force and pressure measured over time. It can be either *quasi-static* (contact force and pressure change slowly over contact time; no distinct global maximum) or *dynamic* (contact force and pressure oscillate quickly over contact time; distinct global maximum);

b) Spatial configuration – indicates the presence or absence of rigid obstacles that can restrict the ability of the human body to recoil. It can be either *constrained* (obstacle restricts body part from recoiling; body part is pinched) or *unconstrained* (no obstacle; body part can recoil).

NOTE 1   A condition for unconstrained spatial configurations is the free distance to the next fixed object or obstacle which is at least 500 mm. More precise distance values can be found in ISO 13854.

All possible combinations of the key contact characteristics lead to the following contact types:

1) Push – robot moves against the moveable and spatially unconstrained body part. The force and pressure increase slowly with time while the robot continues to move (i.e., quasi-static load profile). When the body part contacted has the same speed as the robot, the force or pressure remains at a constant level;

2) Pinch – robot moves against the unmovable and spatially constrained body part. The force and pressure increase slowly with time and remains at a constant level once the robot has stopped (i.e., quasi-static load profile);

3) Impact – robot moves against the moveable and spatially unconstrained body part. The force and pressure increase quickly with time and decrease quickly to zero after reaching its maximum (i.e., dynamic load profile);

4) Crush – robot moves against the unmovable and spatially constrained body part. The force and pressure increase quickly with time (i.e., dynamic load profile) and remains at a constant value after reaching its maximum once the robot has stopped.

NOTE 2   A quasi-static load profile typically occurs when a robot moves against a body part at lower speeds (i.e., driving forces dominate). A dynamic load profile typically occurs when a robot moves against a body part at higher speeds (i.e. inertial forces dominate).

Figure 1 assigns the expression to both key contact characteristics and illustrates typical courses of the contact force.
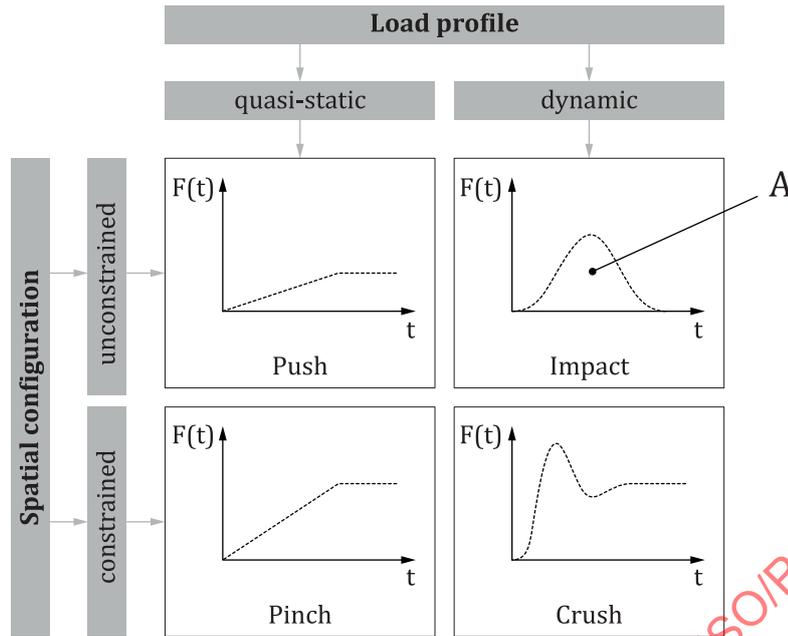
Key

A   illustration of the contact force plotted as a function of time

Figure 1 — Key contact characteristics of contact hazards and their relation to specific contact types

The contact type *push* typically does not need to be tested unless the risk assessment specifies otherwise. The risk from such contacts is typically low since the human will be able to release the contact easily. In case the risk assessment specifies a push relevant for testing, this contact type shall be treated as a pinch. All other contact types shall be assessed through measurement unless the risk assessment specifies otherwise.

4.3   Contact locations

Contact hazards typically occur on moving parts of the robot such as:

— Links, joints, housing of the robot;

— End-effector;

— Workpiece handled by robot;

— Other periphery (e.g. dress packs).

Contacts can also occur with structures in the environment of the robot. Especially before testing pinch or crush points, it should be identified if the contact surface with the smallest curvature radii is on the robot or on the obstacle in the environment of the robot. The pressure shall be measured on the outward part of the surface with the smallest curvature radii.

5   Measuring instrument

5.1   General

This document addresses only the mechanical response of a PFMD to contact and does not describe a specific design of a PFMD. The response of a PFMD can be expressed by a function of contact force over deformation. Like biomechanical response curves, the function describes the contact force that occurs at a specific deformation of the human body part and vice versa.

In context of a PFMD, the contact force is the force measured by a PFMD force sensor. As for human tissue, the force acting on a PFMD causes a deformation of its elastic components. A properly designed and/or configured PFMD should replicate a given biomechanical response curve within the allowable design tolerances specified in 5.2.
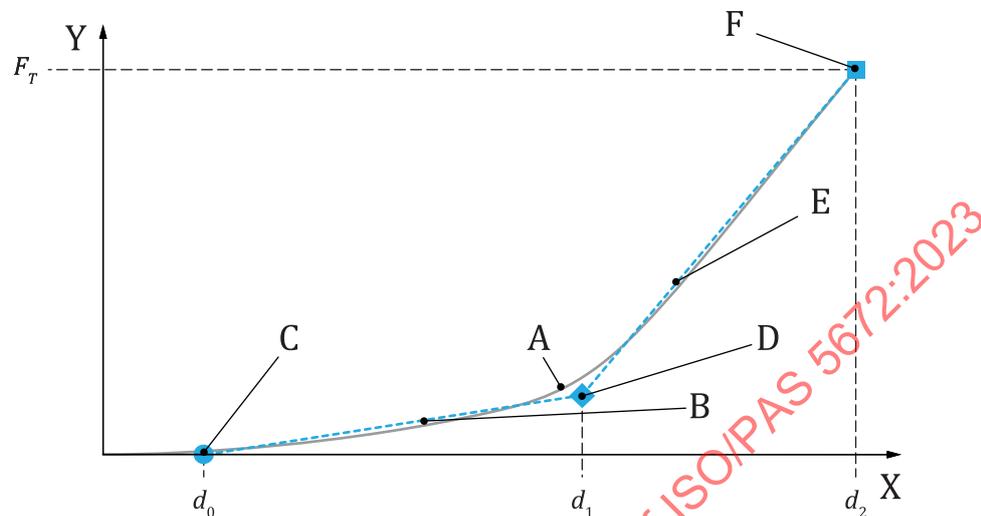
Key

X   deformation of a human body part under contact force

Y   contact force applied to a human body part

F_T force limit for transient contact phase

A   response curve as derived from the same biomechanical data that were used to determine the transient force limit

B   first line that approximates the first part of a response curve (i.e., from d_0 to d_1)

C   point (d_0) at which the first line intersects with the deformation axis

D   point (d_1) at which both lines intersect

E   second line that approximates the second part of the response curve (i.e., from d_1 to d_2)

F   point (d_2) at which the second line intersects the transient force limit

Figure 2 — Illustration of a typical response curve for a specific human body part

Figure 2 displays a typical biomechanical response curve. Every curve is only valid for a specific human body part and shall be developed from the same data from which the applicable transient force limit was derived. When comparing a PFMD response with the reference response from biomechanical experiments, the response curve of the PFMD shall be measured with an indenter (i.e., contact body or probe) with the same characteristics as the one that is specified by the source that provides the biomechanical response curves.

As shown in Figure 2 by (D), a response curve can be divided into two parts. In the first part of the response curve, the contact force increases slightly as the deformation increases until the deformation reaches a characteristic point. This part of the response typically contributes little to the overall response and the maximum contact force. After the characteristic point, the response curve becomes steeper. This steeper part of the response curve shall extend at least to the transient force limit to be applied for the body part replicated by the curve.

5.2   Design parameters

To obtain a minimum number of numerical parameters for properly designed PFMDs, a response curve shall be approximated by two lines. The first line shall approximate the first part of the response curve (from d_0 to d_1). It intersects with the abscissa (deformation axis) at d_0 with $d_0 \geq 0$. An intersection should not occur for negative deformation values. The first line shall end at the characteristic

deformation (d_1) at which the response curve becomes steeper, and the second approximation line begins. Let d be the deformation variable, then the first line is defined by:

$$F_1(d) = c_1 \times (d - d_0) \tag{1}$$

for any deformation (d) between d_0 and d_1, i.e., $d_0 \leq d \leq d_1$.

The second line shall approximate the second part of the response curve (from d_1 to d_2). It begins at the point at which the first line ends per definition (d_1) and ends at the point (d_2) at which it intersects the transient force limit. Then, the second line is defined by:

$$F_2(d) = c_2 \times (d - d_1) + F_1(d_1) \tag{2}$$

for any deformation (d) between d_1 and d_2, i.e., $d_1 < d \leq d_2$.

Both deformation intervals, defined by Formulae (1) and (2), give the following parameters for a properly designed PFMD:

D_1 Distance between d_0 and d_1, i.e., $D_1 = d_1 - d_0$

c_1 Slope of the first line

c_2 Slope of the second line

NOTE   The PFMD design parameters and the biomechanical limits belong together and thus have ideally to come from the same source.

Specific values for these parameters are only valid for a particular human body part. They should, therefore, be provided in combination with the limits for the associated human body part.

5.3 Calibration

For calibration, a PFMD response curve shall be measured using an indentation system that displaces the PFMD at a constant indentation speed of 1 mm/s until the contact force reaches the transient force limit that is given for the body part. During the calibration, force and deformation shall be measured with a sampling frequency of $\geq 100\,\text{Hz}$ and at a resolution of $\leq 1\,\text{N}$ and $\leq 0,1\,\text{mm}$. Signal filters shall not be applied. The contact body that transfers the force from the indentation system to the PFMD shall be the same as the one indicated by the source of the reference response curves or curve parameters.

Once the response curve is measured accordingly, it shall be approximated by two lines. The first line shall approximate the first of the response curve (from d_0 to d_1) and the second line the second part (from d_1 to d_2). For the approximation of the first part, the starting slope ($\tilde{c}_1$) shall be used. For the approximation of the second part, the end slope ($\tilde{c}_2$) shall be used. Figure 3 illustrates the approximation procedure. The intersection of both lines gives parameter $\tilde{D}_1$.

The parameter values from the measured response curve shall then be compared with the parameter values from the reference response curve. Each shall apply to the following conditions:

a) $\tilde{D}_1 \leq D_1$ (i.e. $\tilde{D}_1$ shall not exceed D_1 from the reference response curve)

b) $\tilde{c}_1 \times \tilde{D}_1 \leq c_1 \times D_1$ (i.e. the product of $\tilde{c}_1$ and $\tilde{D}_1$ shall not exceed the product of c_1 and D_1)

c) $\tilde{c}_2 \geq 0,75 \times c_2$ (i.e. $\tilde{c}_1$ shall be equal to or higher than 75 % of c_2)

NOTE   The slope of the first approximation line ($\tilde{c}_1$) taken from the measured response curve can be lower than c_1. It is, however, not recommended for avoiding a loss of robot efficiency. Same applies to the slope of the second approximation line ($\tilde{c}_2$) which can but should not exceed c_2.

According to conditions a) and b), it is acceptable not to replicate the flat part of the reference response curve (i.e., $\tilde{D}_1 = 0$ and $\tilde{c}_1 = 0$). Omitting this part of the response curve can be necessary, when its replication is not possible because of technical constraints or other boundaries.
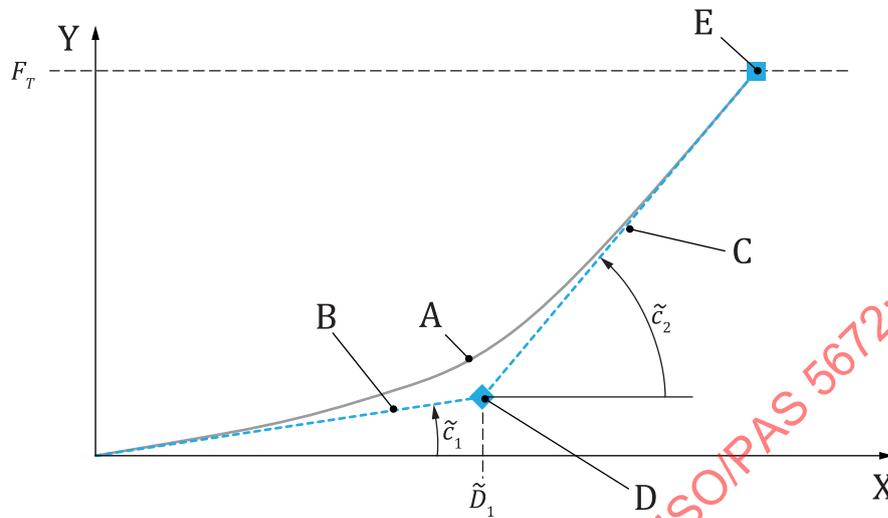
Key

X	deformation	C	second line that has the end slope of the response curve where it intersects with the transient force limit (F_T)
Y	contact force	D	intersection of the first and second line
A	mechanical response curve measured with a PFMD	E	intersection of the second line with the transient force limit (F_T)
B	first line that has the starting slope of the response curve measured		

Figure 3 — Calibration parameters derived from a PFMD response curve

5.4 Sensor characteristics

5.4.1 General

Sensors used for pressure and/or force measurement can be sensitive to ambient temperature and humidity. The instructions given by the sensor manufacturer shall be studied and followed accordingly.

All sensors shall be calibrated as specified by their manufacturers. Moreover, they shall also be calibrated in accordance with all applicable standards that specify the design of PFMD used for testing.

Sensors used for force and pressure measurement should have a calibrated maximum measurement range that exceeds the highest biomechanical limits at least by 20 %.

Force signals and continuously measured pressure signals (see 5.4.3) shall both be filtered using a Butterworth four-pole phase-less low-pass filter with a cut-off frequency of 100 Hz and stop damping of -30 dB.

NOTE   Filter configuration corresponds to a CFC 60 filter as specified in ISO 6487. An exemplary filter implementation can be found in ISO 6487:2015, Annex A. A CFC 60 filter will have only an effect on pressure signals if these signals were sampled with frequencies of $\geq 600\,\text{Hz}$.

5.4.2 Force sensors

Sensors used for force measurement shall sample the force at a frequency of 1 kHz or higher. The resolution of the force measurement shall be $\leq 1\,\text{N}$.

5.4.3 Pressure sensors

Sensors made for pressure measurement can either implement peak measurement or continuous measurement. For peak measurement, the pressure sensor captures only the peak pressures that appear in the pressure measurement area of the sensor. Consequently, the global maximum pressure p_{max} (highest pressure in the contact area) measured by such sensors belong to both, the transient and quasi-static contact phase. For continuous measurement, several separate force cells, equally distributed within the sensing area, record the pressure over time. Sensors used for continuous pressure measurement shall sample the pressure at a frequency of $\geq 250\,\text{Hz}$. The measurement resolution shall be $\leq 1\,\text{N}\,/\,\text{cm}^2$.

Sensors used for pressure measurement shall sample the pressure with the same or higher spatial resolution that is indicated in the source of the pressure limits. If pressure sensors with higher resolutions are used, the spatial resolution should be reduced to the resolution given in the source of the pressure limits. A technique to reduce the spatial resolution is described in Annex B.

NOTE   The pressure values used as the foundation for the pressure limits listed in ISO/TS 15066 were recorded with a spatial resolution of one pressure measurement value per mm² (i.e., 25 DPI or dots per inch).

6 Measurement methods

6.1 General

In contact tests with robots, a PFMD that is fixed to a rigid structure typically measures a force signal similar in shape to the curve displayed in Figure 4. For the assessment of such a measurement result, the curve shall be divided into a transient contact phase and quasi-static contact phase.

NOTE   The transient and quasi-static contact phases are typical stages of a contact as exhibited by the force or pressure measured over time. These phases do not indicate the type of contact as specified in 4.2.

Unless otherwise specified, the transient contact phase begins at the initial contact threshold where the force reaches 5 N and ends after 500 ms. During the transient contact phase, the force builds up quickly and typically decreases immediately after reaching a maximum. The maximum force in the transient contact phase shall be extracted as the maximum transient force (F_{TR}).

The quasi-static contact phase begins at the end of the transient contact phase, i.e., 500 ms after initial contact. It ends when the residual fluctuation of the force signal drops below twice the required measurement resolution (see 5.4.2). At the end of this phase, the force is considered to have settled. The maximum force in the quasi-static contact phase shall be extracted as the maximum quasi-static force (F_{QS}).

When using continuous pressure measurement (see 5.4.3), the maximum pressure in the transient contact phase shall be extracted as the transient peak pressure (p_{TR}) and the maximum pressure in the quasi-static contact phase shall be extracted as the quasi-static peak pressure (p_{QS}). When using peak pressure measurement, the overall pressure maximum p_{max} shall be extracted and used as p_{TR} and p_{QS}.
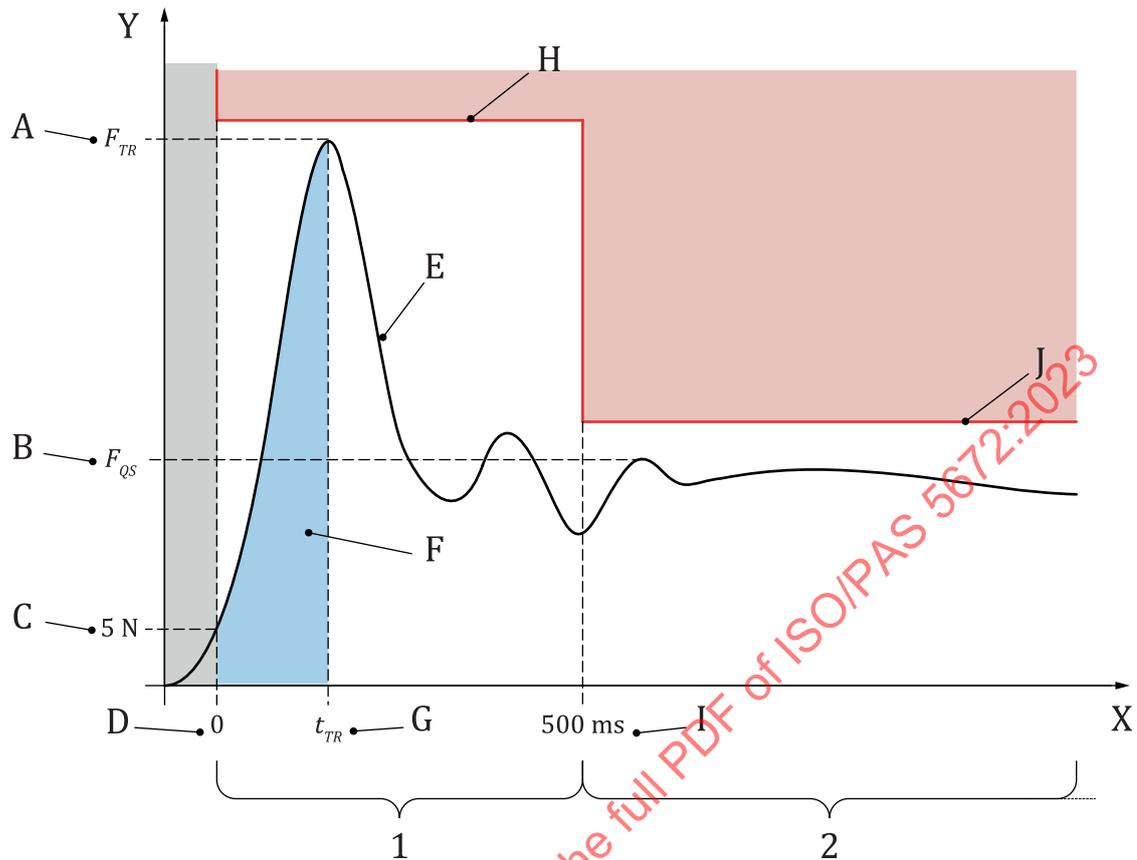
Key

X	time	F	area from initial contact to the global maximum force of both phases
Y	force	G	time at which the force reaches its maximum (F_{TR})
A	maximum transient force	H	transient force limit
B	maximum quasi-static force	I	end of the transient contact phase
C	initial contact threshold (5 N)	J	quasi-static force limit
D	initial contact (0 s)	1	transient contact phase
E	force signal plotted as a function of time	2	quasi-static contact phase

Figure 4 — Typical trace of a force signal measured by a fixed PFMD during contact testing (maximum area pressure, if measured over time, will deliver a similarly shaped trace)

Depending on the robot motion and the testing conditions, the shape of the force signal can significantly differ from the shape displayed in Figure 4. Two examples of force signals with different shapes are displayed in Figure 5. Variations of them or completely different shapes can occur.
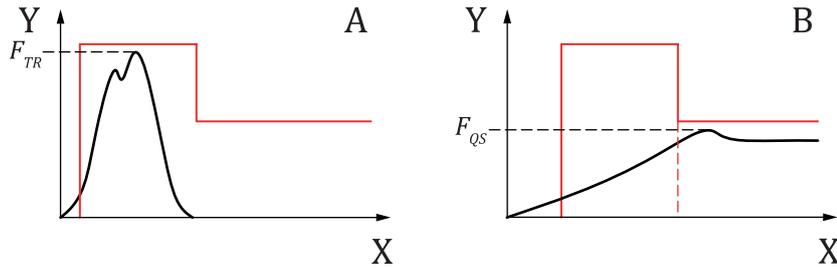
Key

X   time

Y   force

A   contact has no quasi-static phase (quasi-static maximum force is zero $F_{QS} = 0$ and quasi-static maximum pressure is zero $p_{QS} = 0$)

B   contact has no transient phase (transient maximum force and transient maximum pressure can be ignored because the quasi-static maximum force and quasi-static maximum pressure are higher)

Figure 5 — Exceptional force-time traces of contact hazards (maximum area pressures, if measured over time, will deliver similarly shaped traces)

6.2 Pinch and crush

6.2.1 General

To measure a pinch or a crush (see 4.2), the PFMD shall be affixed to solid and rigid structures or obstacles that exist in the robot environment. If such structures do not exist, a rigid supportive structure for holding the PFMD in place shall be created. The supportive structure should be as stiff as possible. Annex A provides some examples of properly designed support structures.

The support structure should be at least twenty times stiffer than the PFMD.

6.2.2 Limited space for PFMD installation

Depending on the dimensions of the robot and surrounding structures, the space around a pinch or crush zone in the collaborative application under test can be limited and not accommodate a PFMD. When this is the case, the steps illustrated in Figure 6 shall be followed in the given order. A PFMD that fits into the limited space shall be used whenever possible.

The steps illustrated in Figure 6 shall be followed only for testing pinch points. If the contact can occur within the structure of the robot, the forces and pressures can become large and shall be measured with a suitable PFMD that fits into the robot structure. Pinch points within the robot structure can occur, for example:

— between links of an articulated robot manipulator,

— within a robotic gripper, or

— between a workpiece and part of the gripper.

The first step that shall be taken to measure force and pressure in small spaces is to modify the environment of the robot. It shall be verified if surrounding structures of the robot can be removed so that the PFMD can be placed properly. If modifications to the environment are not possible, the justification for this shall be documented in the test report. Afterwards, it shall be verified if the robot has symmetries (e.g. around a joint axis) and if these can be used to install the PFMD at a location with more space. Most robot manipulators can be rotated around their first axis without changing their parameters that affect the contact forces and pressures. Mobile platforms can usually be rotated around their centre axis. The robot manufacturer should be contacted to figure out if the robot has

helpful symmetries. Otherwise, the absence of symmetries shall be documented in the test report. As the last possibility to execute the test, the contact point shall be relocated to a location with sufficient space in which testing is possible under almost equal conditions. The decision and the reasons that led to this equivalent point shall be documented in the test report.

If measurement is not possible other assessment methodologies shall be applied.
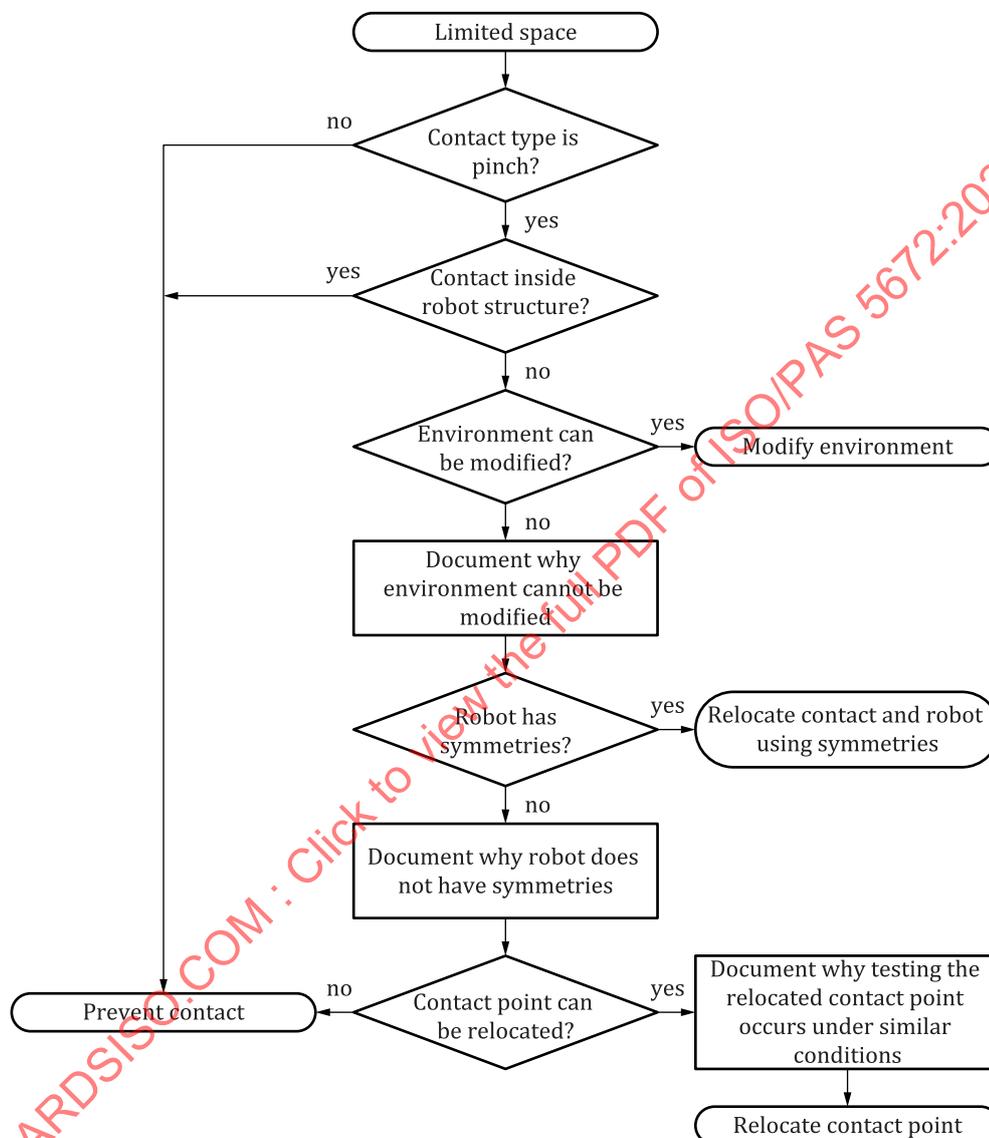
Figure 6 — Procedure to follow when a PFMD cannot be installed at the testing point due to limited space.

6.3 Impact

6.3.1 General

There are two methods to measure impact. The first method utilizes a PFMD with a movable measuring unit and the second a fixed PFMD with a mathematical conversion technique.

6.3.2 PFMD with a moveable measuring unit

A moveable PFMD has a measuring unit that is not affixed to a rigid supportive structure and, thus, can freely move in the direction of the force that the robot exerts on the PFMD. If such a PFMD is used, the

total mass of the moveable measuring unit shall match the effective mass of the human body part under test.

NOTE 1   Most PFMD with movable measuring units only allow for measuring impacts in the horizontal plane. In the event an oblique impact will be measured, the conversion technique described in 6.3.3 is used instead of the PFMD with a movable measuring unit.

NOTE 2   Segment masses for various human body parts can be found in ISO/TS 15066.

NOTE 3   A PFMD with a moveable measuring unit cannot be used to assess crush.

6.3.3   Fixed PFMD and conversion technique

When testing impacts with a PFMD that does not have a moveable measuring unit and, thus, affixed to a rigid structure, the following mathematical conversion technique should be used. The conversion technique converts the results measured with a fixed PFMD into results like those measured with a PFMD with a moveable measuring unit.

The conversion technique uses a scaling factor S that indicates the ratio of the measurement value recorded with a movable PFMD to that recorded with a fixed PFMD. The scaling factor is given by:

$$S = \sqrt{\frac{m_H}{m_H + m_R}}$$

where

m_H is the effective mass of the colliding human body part;

m_R is the effective mass of the robot under test.

The effective human body mass m_H is typically provided together with the biomechanical limits for the body locations to be tested.

If the effective robot mass m_R is unknown, it can be estimated from the force signal measured by the PFMD as follows:

$$m_R \approx \frac{I_R}{v_R}$$

where

I_R is the momentum (in newton seconds [Ns]) of the robot;

v_R is the speed (in meters per second [m/s]) of the robot before initial contact.

The momentum (I_R) of the robot coincides with the area below the force signal curve between initial contact ($t = 0\,\text{s}$) to the maximum force in the transient contact phase (F_{TR}) that occurs at t_{TR}. In Figure 4, this area is marked in blue. The conversion technique shall not be applied if the maximum force does not lie in the transient contact phase (as displayed in Figure 5, B).

The momentum of the robot I_R can be estimated by:

$$I_R \approx \frac{1}{2} F_{TR} t_{TR}$$

where

F_{TR} is the maximum force in the transient contact phase (in newtons [N]) measured;

t_{TR} is the time (in seconds [s]) at which F_{TR} occurs (shall be $\leq 500\,\mathrm{ms}$).

A more precise estimation of the momentum of the robot I_R can be calculated by:

$$I_R \approx \int_0^{t_{TR}} F(t)\,dt$$

where $F(t)$ is the contact force (in newtons [N]) measured over time.

The measured speed of the robot should be used for v_R. Alternatively, the maximum speed as monitored by the safety functions may be used.

Unless not specified otherwise, the scaling factor S shall not be lower than $S_{lim} = 0{,}15$ (lower boundary).

$$S_{lim} \leq S < 1$$

The scaling factor S shall be multiplied with the maximum transient force F_{TR} measured with the fixed PFMD to achieve the projected maximum transient force $\tilde{F}_{TR}$:

$$\tilde{F}_{TR} = S \times F_{TR}$$

If pressure sensors for continuous measurement are used (see 5.4.3), the scaling factor S shall be multiplied with the maximum transient pressure p_{TR} to receive the projected maximum transient pressure $\tilde{p}_{TR}$:

$$\tilde{p}_{TR} = S \times p_{TR}$$

If pressure sensors for peak measurement are used (see 5.4.3), the scaling factor S shall be multiplied with the overall maximum pressure p_{max} to receive the projected maximum pressure $\tilde{p}_{max}$:

$$\tilde{p}_{TR} = S \times p_{max}$$

6.4 PFMD position

During a test, the contact area shall be centred on the measurement area of pressure sensor. Additionally, the measurement area of the pressure sensor shall accommodate the entire contact area as illustrated in Figure 7 (B). The contact area or pieces of it shall never exceed the measurement area.

Most sensors for pressure measurement are designed as a thin film that can bent around one axis. During a test, significant deformation of the film should be avoided to avoid unrealistic high pressures in the heavily deformed or wrinkled areas.
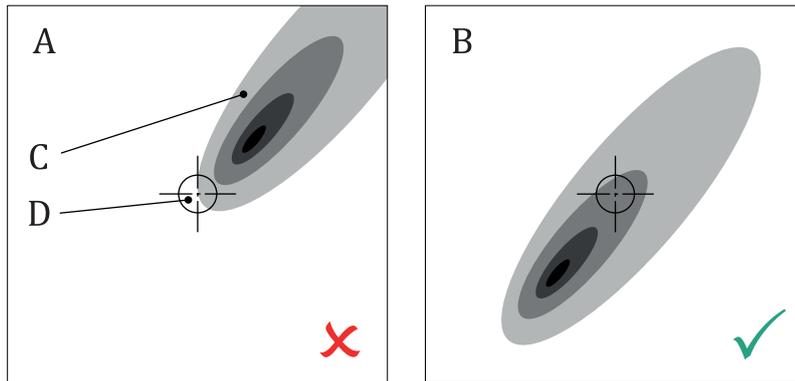
Key

A   contact is not entirely covered by measurement area of the pressure sensor

B   contact is entirely covered by measurement area of the pressure sensor

C   contact area

D   centre of the measurement area of the pressure sensor

Figure 7 — Typical pressure images that can result from different positions of the PFMD pressure measurement area

The orientation of the PFMD with respect to the contact surface of the robot should be as perpendicular as possible to avoid shear forces.

7 Measurement procedure

7.1 General

Firstly, switch on the robot and wait until all systems acknowledge that they are running correctly. The robot should remain switched on until it is fully warmed up. If possible, all technical measures that are not implemented as a safety function or as a safety function with the performance level and implementation category required for the collaborative application shall be switched off or removed prior to the tests.

NOTE 1   According to ISO 12100:2010, 3.30, a safety function is defined as a function whose failure can result in an immediate increase of the risk(s).

NOTE 2   According to ISO 10218-2, the safety functions used in a collaborative application comply with performance level PL d and implementation category 3 as specified by ISO 13849-1. All other technical measures that are either not implemented as a safety function or that do not comply with the required performance level and implementation category shall be removed or switched off before the collaborative application is tested. For example, a tactile sensor for contact detection with PL b and cat. 2, if used in the collaborative application, has to be switched off or removed. Another example would be acceleration sensors designed for motion tracking that have to be switched off if they are used for implementing a contact detection function.

The following describes the procedure for performing contact measurements under identical testing conditions. Testing under identical conditions means to repeat the measurement of the same contact hazard several times with the same PFMD configuration. The PFMD configuration is given by the design parameters of the device that replicate the biomechanical response of one body location or body part (see 5.2)

Annex C and Annex D provide different examples that describe the measurement procedure for specific collaborative applications.

7.2   Test preparation

7.2.1   General

The following general steps shall be followed to prepare for the test:

a)   If necessary, configure the PFMD to the body region or body locations to be tested;

b)   If necessary, install the pressure sensing film on the impact side of the PFMD;

c)   Locate the contact area as given by the risk assessment;

d)   Move the robot along the programmed path to the point where the contact hazard can occur.

7.2.2   Contact area lies on the robot

If the contact area lies on the surface of the robot or on the end-effector, the following steps shall be followed to further prepare for the test:

a)   Mount the PFMD on a rigid support frame (see 6.2 or 6.3);

b)   Position the PFMD so that the robot almost touches the impact side of the PFMD in the centre and the contact area lies entirely within the measurement area of the pressure film (no overlapping, see 6.4).

7.2.3   Contact area lies in the environment

If the contact area lies on the surface of environmental structures, the following steps shall be followed to further prepare the test:

a)   Turn the PFMD with its impact side against the contact area to be tested;

b)   Position the PFMD so that the robot almost touches the bottom of the PFMD in the centre (see 6.4);

c)   Ensure that the PFMD is properly mounted on a rigid support frame, but still able to move in the direction of the force transferred by the robot.

7.3   Test execution

The following steps shall be followed to execute the test:

a)   Move the robot to the starting position so that the distance between starting and contact position allows the robot to reach the programmed speed before it collides with the PFMD at the desired position;

b)   Start recording of force and, if applicable, pressure;

c)   Once the sensors begin to record, start the movement of the robot;

d)   After the robot collides with the impact side of the PFMD, record the signals;

e)   Release the robot from contact by moving it backwards (e.g. via manual control);

Steps a) to e) shall be executed at least three times (see 7.4).

7.4   Analysis

Before analyzing the data, all signals shall be filtered as described in 5.4. Afterwards, the signals shall be grouped in samples so that a single sample only contains signals from measurements that belong to the same test series (see 7.3) and have thus been carried out under identical conditions.

From here on, variable x will be a measurement value that corresponds to one of the following maximum values:

— F_{TR} (maximum force in the transient contact phase);

— F_{QS} (maximum force in the quasi-static contact phase);

— p_{TR} (maximum pressure in the transient contact phase);

— p_{QS} (maximum pressure in the quasi-static contact phase;

— $\tilde{F}_{TR}$ (maximum transient force in the projected transient contact phase; see 6.3.3);

— $\tilde{p}_{TR}$ (maximum transient pressure in the projected transient contact phase; see 6.3.3);

— p_{max} (maximum pressure as measured by pressure films for peak pressure measurement).

For all contact types (see 4.2), contact phases (see Figure 4), PFMD types (see 6.3) and pressure measurement principles (see 5.4.3), Table 1 breaks down which of the values listed above shall be used as measurement value x.

Table 1 — Mapping of the maximum values for all contact types, contact phases, PFMD types, and pressure measurement principles

Contact type	Contact phase	Force	Pressure (continuous measurement)	Pressure (peak measurement)
Pinch and crush	Transient contact phase	$x = F_{TR}$	$x = p_{TR}$	$x = p_{max}$
	Quasi-static contact phase	$x = F_{QS}$	$x = p_{QS}$	$x = p_{max}$
Impact (fixed PFMD; see 6.3.3)	Transient contact phase	$x = \tilde{F}_{TR}$	$x = \tilde{p}_{TR}$	$x = \tilde{p}_{max}$
	Quasi-static contact phase	$x = 0$	$x = 0$	$x = 0$
Impact (moveable PFMD)	Transient contact phase	$x = F_{TR}$	$x = p_{TR}$	$x = p_{max}$
	Quasi-static contact phase	$x = 0$	$x = 0$	$x = 0$

If at least five measurement values have been recorded under identical conditions, 20 % of the highest values and 20 % of the lowest values should be discarded to remove top and bottom outliers. The number of maximum and minimum values to be discarded can be calculated by:

$$N_D = 0,2 \times N$$

where

N_D is the number of bottom and top outliers to be discarded;

N is the total number of measurement values.

The value of N_D shall be rounded to the lower integer. Table 2 indicates the number of top and bottom outliers that should be removed depending on the number of measurements recorded in a test.

Table 2 — Number of top and bottom outliers that should be discarded

Number of meas. values	Bottom outliers to be discarded	Top outliers to be discarded
≥ 5	1	1
≥ 10	2	2
≥ 15	3	3
⋮	⋮	⋮

After discarding outliers, the following values shall be calculated from the remaining measurement values:

Mean:

$$\mu_X = \frac{1}{N}\sum_i^N x_i = \frac{1}{N}(x_1 + x_2 + \ldots x_N)$$

Standard deviation (STD):

$$\sigma_X = \sqrt{\frac{1}{N-1}\sum_i^N (x_i - \mu)^2} = \sqrt{\frac{1}{N-1}\left[(x_1 - \mu)^2 + (x_2 - \mu)^2 + \ldots (x_N - \mu)^2\right]}$$

Normalized standard deviation:

$$\tilde{\sigma}_X = \frac{\sigma}{\mu} \times 100\,\%$$

Variable x refers to any of the measurement values (F_{TR}, p_{TR}, F_{QS} and p_{QS}) as mentioned above. Based on the normalized standard deviation $\tilde{\sigma}$ and mean μ, the following criteria indicate the overall test result:

Criterion 1 The normalized standard deviation calculated from measurement values x_i based on maximum forces should not exceed 5 % ($\tilde{\sigma}_F \leq 5\,\%$). The normalized standard deviation calculated from measurement values x_i for maximum pressures should not exceed 10 % ($\tilde{\sigma}_p \leq 10\,\%$). Higher normalized standard deviations indicate that the design of the measurement setup is improper and thus impairs the repeatability of the measurement. In this case, the measurement setup should be improved.

NOTE   Vibrations in the mechanical measurement setup can be responsible for scattered measurement values and thus high standard deviations. To minimize vibrations, it can be helpful to follow the guidelines given in Annex A.

Criterion 2 The mean μ_X calculated from the measurement values x_i shall not exceed the applicable biomechanical limit value to consider the test passed. Otherwise, the test is not passed.

7.5 Test report

The header of the test report shall contain the following general information (see Annex E):

— Information about the recipient;

— Information about the person who executed the tests;

— Reference to this document and International Standards used (including year of publication);

— Place and date of the tests;

— Brief description of the collaborative application (including robot system under test);

— Brief description of the testing equipment.

The main part of the report shall contain the following items for each contact hazard:

a) Brief description of the contact hazard, including but not limited to the following conditions:

   — situation that precedes the hazard,

   — location of the contact point,

— shape of the contact area,

— robot speed (if available);

b) Contact type (see Figure 1);

c) List of body parts subject to potential contact and their associated biomechanical limits for the identified contact type;

d) Measurement method used for impact (if applicable);

e) If an impact was tested using a PFMD without a movable measuring unit: scaling factor as determined by the conversion technique, including maximum transient force and maximum transient pressure calculated, obtained from the scaling factor;

f) Normalized standard deviations for both quantities (force and pressure) and contact phase (transient and quasi-static), including a reference to this document, subclause 7.4;

g) Means for both quantities (force and pressure) and contact phases (transient and quasi-static), including a reference to this document, subclause 7.4.

Result from verifying test criteria (see 7.4).

NOTE   The risk assessment typically identifies some of the items listed above.

The main part of the report should contain the following additional information:

— Picture that displays the contact situation and location of the contact area on the robot and/or environment;

— List with all measurement values recorded in the test;

— Outliers that were discarded (if available);

— Summary of the tests that were passed and the tests that were not passed;

— Deviations from the test procedure (if applicable);

— Unusual features observed during the test (if applicable).

Annex E provides a template to document test results.

Annex A
(informative)

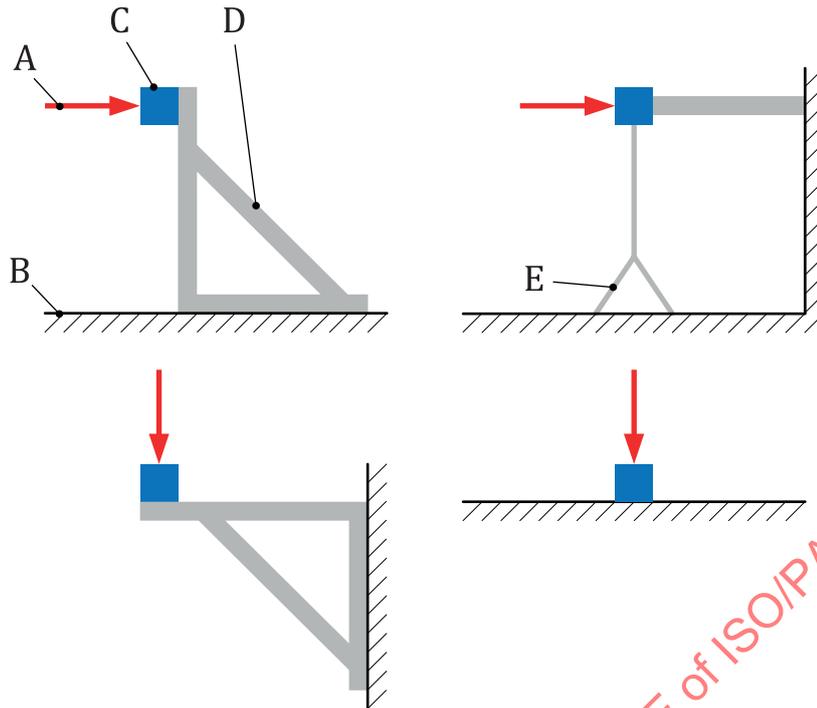## Rigid support structures for PFMD installation

A.1 General

The PFMD is mounted to a rigid support structure that secures it from displacement and vibration when testing for a pinch and a crush. The following describes some variants to mount and orient the PFMD properly for different conditions. Other variants are possible.

An indicator for inappropriate mounting is high vibrations in the force signals or high relative standard deviation values that exceed the recommended thresholds for force and pressure (see criteria 1 in 7.4).

A.2 Support structures

The stiffness of a PFMD mounting or support structure can significantly affect the repeatability and thus the standard deviation of measurement values that were recorded under identical test conditions. If the PFMD is mounted on an elastic support structure, attached to a loose obstacle, or even held by hand, it is likely that the normalized standard deviation exceeds a certain threshold (see 7.4). A properly designed support structure has at least twenty times the stiffness of the attached PFMD to hold the PFMD in position during impact tests. Figure A.1 gives some examples of suitable structures for different testing conditions.

Key

A   moving direction of the robot under test

B   ground / structure on which the robot is moving and the support structure mounted

C   pressure-force measurement device

D   support structure made of metal beams

E   tripod / stand holding the PFMD

Figure A.1 — Proper designs for support structures that secure a PFMD against displacements or vibrations

A.3 Orientation and position aids

The contact surface on the robot should move perpendicular towards the impact side of the PFMD. To ensure full perpendicularity, the possibility to precisely adjust the angle of the PFMD to the movement of the contact surface on the robot can be sometimes necessary. One possibility to orient a PFMD is to install it on a lockable ball-joint mount as illustrated in Figure A.2.

Key
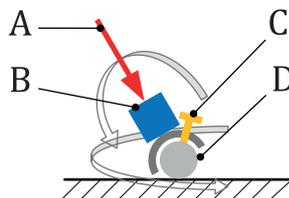
A   moving direction of the robot under test

B   pressure-force measurement device

C   locking screw

D   ball-joint mount (can be turned around all axes)

Figure A.2 — Ball-joint mount for adjusting the orientation of a PFMD

Another robot can be used if full flexibility is required to adjust position and orientation of a PFMD. Alternatively, it is possible to mount the combination of a PFMD and a ball-joint mount on a forklift. The forklift can be used to adjust the position and the ball-joint mount to adjust the orientation. Regardless

of which device is used, it is highly recommended that the stiffness of the device complies with the specifications given in A.2.

In the event of testing for a pinch or a crush, it is possible that the contact surface on the environmental obstacle, that prevents the human body part from moving, has a smaller curvature radius than the contact surface on the robot. In this case, it is most likely that the contact surface on the environment will cause higher pressures than the contact surface on the robot. Under such circumstances, the PFMD should be turned with the impact side towards the critical surface on the obstacle in the environment. Alternatively, the PFMD can be mounted on the robot so that the robot is pressing it against the surface on the obstacle during the test (see 7.2). Mounting the PFMD on a robot will however increase the apparent robot mass. Especially for crush hazards, the increased apparent robot mass will represent a conservative test case that will most likely result in higher maximum forces and pressure compared to those that would be measured under normal conditions (PFMD not mounted on the robot).

Annex B
(informative)

Reduction of pressure image resolution

B.1 General

Systems for pressure measurement usually store the pressure signal as a series of images (for continuous measurement) or a single image (for peak measurement). Each pressure image has a specific resolution that impairs the ability of the sensor to acquire pressures in spots that have smaller dimensions as the fields in the virtual grid spanned by the resolution. It is therefore recommended to use a downscaling technique that reduces the resolution of the pressure images measured by a PFMD to the resolution that is reported in the source of the pressure limits. Since downscaling will ultimately lead to slightly smaller pressures, it should only be applied if the resolution of the pressure sensor used is higher than the resolution used in the clinical studies that delivered the applicable biomechanical limits.

NOTE   In the reports on the clinical studies conducted by University Mainz[12] and Fraunhofer IFF,[10,11] a pressure sensor with one data point per mm^2 (i.e. 25 DPI or dots per inch) was used.

A recommended downscaling technique is described in the following.

B.2 Averaging filter

It is recommended to apply an averaging filter to the pressure images measured in order to reduce the pressure resolution. Let R_0 be the pressure resolution used to measure the pressure limits and R the pressure resolution of the pressure sensor used with $R > R_0$. The ratio of both is $\rho \in \mathbb{R}$

$$\rho = \frac{R}{R_0}.$$

The floor-rounded value of ρ determines the dimension of the averaging filter matrix $\mathbf{A} \in \mathbb{R}^{n \times n}$

$$a = \lfloor \rho \rfloor = \max\{r \in \mathbb{Z} \mid r \le \rho\}.$$

If a is an even number, the matrix $\mathbf{A}$ has size $n = a + 1$ and the form

$$\mathbf{A} = \frac{1}{(n-1)^2} \mathbf{A}_0$$

where $\mathbf{A}_0$ is

$$\mathbf{A}_0 = \begin{bmatrix} 0,25 & 0,5 & \cdots & 0,5 & 0,25 \\ 0,5 & 1 & \cdots & 1 & 0,5 \\ \vdots & \vdots & 1 & \vdots & \vdots \\ 0,5 & 1 & \cdots & 1 & 0,5 \\ 0,25 & 0,5 & \cdots & 0,5 & 0,25 \end{bmatrix}.$$

The centre of $\mathbf{A}_0$ is filled with "1". The border elements are 0,5 and the corner elements are 0,25.

If a is an odd number, the matrix $\mathbf{A}$ has size $n = a$ and the form

$$\mathbf{A} = \frac{1}{n^2}\mathbf{A}_0$$

where $\mathbf{A}_0$ is a "1"-matrix

$$\mathbf{A}_0 = \begin{bmatrix} 1 & \cdots & 1 \\ \vdots & 1 & \vdots \\ 1 & \cdots & 1 \end{bmatrix}.$$

Let $\mathbf{P}$ the matrix representation of a pressure image of size $M \times N$ measured by the pressure sensor and $p_{ij} := P(i,j)$ an element of $\mathbf{P}$. Then, p_{ij} is also a pixel in the pressure image or, more precisely, a single pressure value in the i-th row and j-th column of $\mathbf{P}$. To apply the average filter $\mathbf{A}$, the corresponding pixel $\tilde{p}_{ij}$ in the newly created downscaled pressure image can be calculated as follows

$$\tilde{p}_{ij} = \sum_{k=1}^{n}\sum_{l=1}^{n}\left\{ a_{kl} \times P\left(i + l - \frac{(n+1)}{2}, j + k - \frac{(n+1)}{2} \right) \right\}$$

with a_{kl} being the element of $\mathbf{A}$ in the k-th row and l-th column. The pixels referred by the indices

$$\left(i + l - \frac{(n+1)}{2} \right) < 0 \quad \text{or} \quad \left(i + l - \frac{(n+1)}{2} \right) > M$$

and

$$\left(j + k - \frac{(n+1)}{2} \right) < 0 \quad \text{or} \quad \left(j + k - \frac{(n+1)}{2} \right) > N$$

lie technically outside the image and is set to "0".

Annex C
(informative)

Example 1: Pick-and-place application

C.1 Example description

This example addresses the measuring methods used to test a pick-and-place application against biomechanical limits. The example does not constitute a complete risk assessment.

The pick-and-place application includes a robot as shown in Figure C.1. The task of the robot is to pick up workpieces from a conveyor, which it then places in a station for quality inspection. After inspection, the robot deposits the workpiece in a tray on a mobile platform and returns to the conveyor position, where the process is repeated.
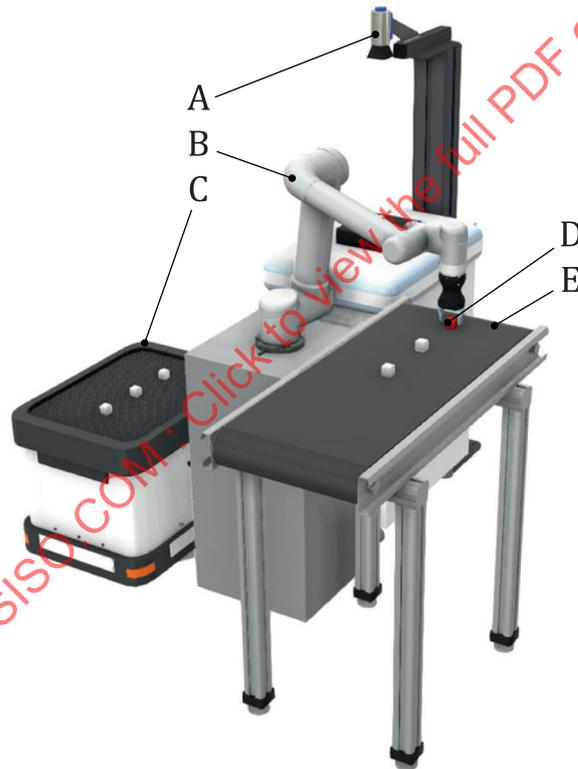
Key

A	inspection station	D	workpiece
B	robot manipulator	E	input conveyer
C	output tray on a mobile platform		

Figure C.1 — Overview of example 1: "Pick-and-Place Application"

Close to the robot in this example, there are several workstations at which humans work. As Figure C.1 displays, the robot is not fenced. To protect the surrounding humans against harmful robot contacts, Power and Force Limiting as specified in ISO 10218-2 and ISO/TS 15066 is implemented as safeguarding

mode. This means that the robot is not allowed to exceed the given biomechanical limits for this application.
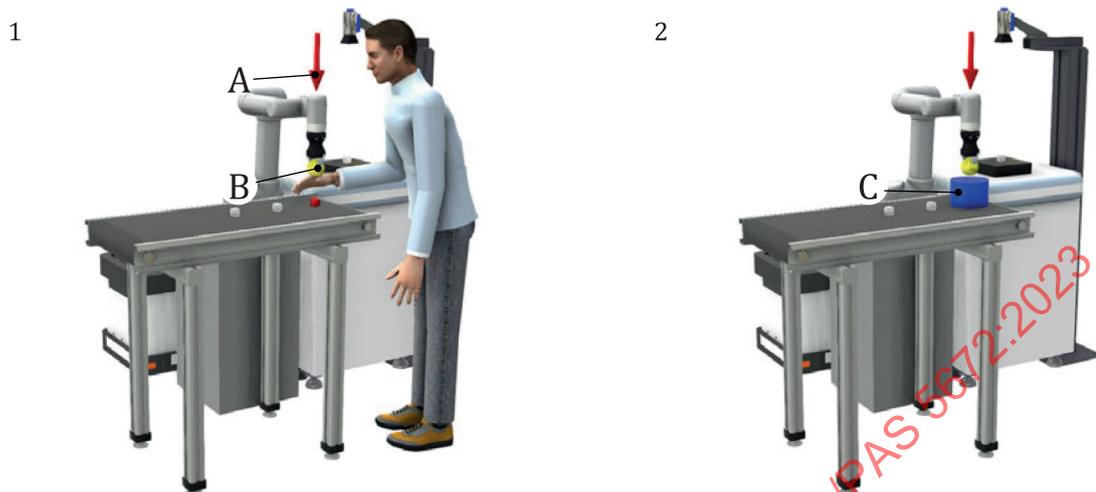
Key

A   moving direction of the robot   C   pressure-force measurement device (PFMD)

B   contact point

Figure C.2 — Example 1 "Pick-and-Place Application": Contact hazard 1 (pinch of the hand when robot approaches workpiece on the conveyer)

The workpieces have rounded edges, measuring 2 mm in radius. All other edges on the robot, grasp-type gripper or surrounding structures have the same or larger radii.
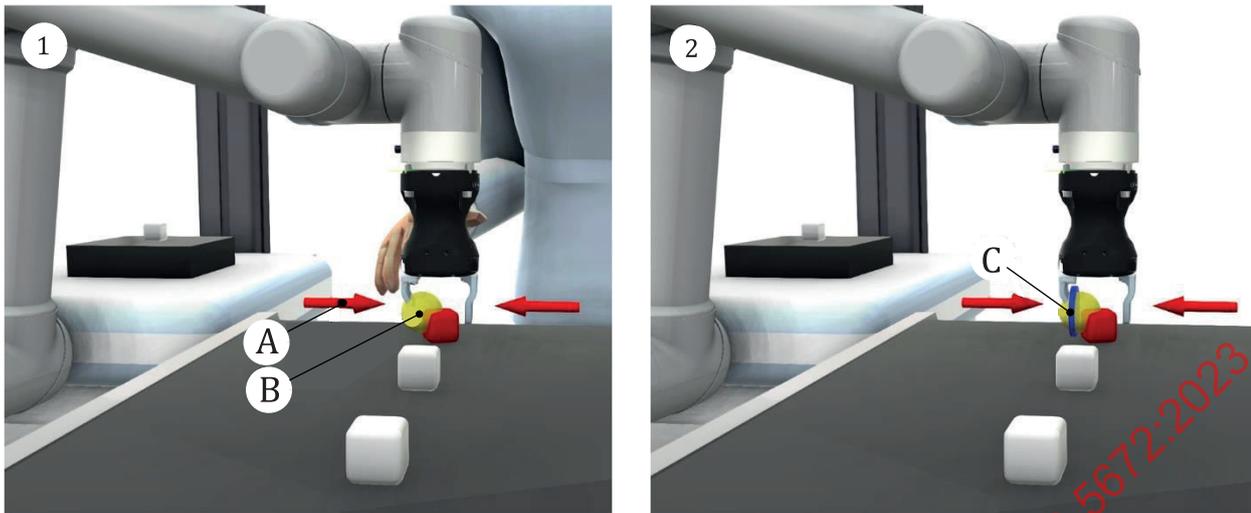
C.2   Contact hazards

The risk assessment done for the pick-and-place robot application has identified the following contact hazards as typical results of reasonably foreseeable misuse or human error (hazard list is not exhaustive):

Description of contact hazard 1 (pinch of the hand when robot approaches workpiece on the conveyer)

If a misaligned workpiece on the conveyer is about to disturb the process, a human bystander can try to correct the position of the workpiece by hand as the robot approaches it. This event of foreseeable misuse can lead to an unintended contact with the human. Since the robot approaches the workpiece slowly and the conveyer constitutes an obstacle that hinders movement of the human body, the type of contact constitutes a pinch. Body locations that can be affected by the impact are radial bone, forearm muscle, forefinger end joint D/ND, and back of the hand D/ND. Figure C.2 (left) illustrates the situation described.

Description of contact hazard 2 (pinch of the fingers when robot closes the grasp-type gripper to pick up a workpiece)

The situation that precedes this hazard is the same as for contact hazard 1. The only difference is that the unintended contact occurs inside the grasp-type gripper as the robot closes its fingers. In this situation, it is possible that the human fingers are pinched between one gripper finger and the workpiece, or even between both gripper fingers. Body locations that can be affected by the pinch contact are forefinger pad D/ND, and forefinger end joint D/ND. Figure C.3 (left) illustrates the situation described.

Key

A   closing direction of the gripper fingers

B   contact point

C   pressure-force measurement device (PFMD) for small spaces

Figure C.3 — Example 1 "Pick-and-Place Application": Contact hazard 2 (pinch of the fingers when robot closes the gripper to pick up a workpiece)

Key

A   moving direction of the robot

B   contact point

C   pressure-force measurement device (PFMD)

D   support structure

Figure C.4 — Example 1 "Pick-and-Place Application": Contact hazard 3 (impact with the upper extremity when robot approaches station for quality inspection)

Description of contact hazard 3 (impact with the upper extremity when robot approaches station for quality inspection)

If the robot accidentally drops a workpiece in the inspection station, a human bystander can try to remove it as the robot approaches the inspection station with another part. This situation can lead to unintended contact with the human shoulder or back. Since the human body can move freely (no obstacles), the type of contact will constitute an impact. Body locations that can be affected by the

impact are shoulder joint, sternum, pectoral muscle, deltoid muscle, and humerus. Figure C.4 (left) illustrates the situation described.

Table C.1 — Body locations that can be subjected to potential contacts identified in the example "pick-and-place robot"

Body Location	Contact Hazard 1 (Pinch)	Contact Hazard 2 (Pinch)	Contact Hazard 3 (Impact)
Forehead			
Temple			
Masticatory muscle			
Neck muscle			
7th cervical vertebra			
Shoulder joint			X
5th lumbar vertebra			
Sternum			X
Pectoral muscle			X
Abdominal muscle			
Pelvic bone			
Deltoid muscle			X
Humerus			X
Radial bone	X		
Forearm muscle	X		
Arm nerve			
Forefinger pad		X	
Forefinger end joint	X	X	
Thenar eminence			
Palm			
Back of the hand	X		
Thigh muscle			
Kneecap			
Middle of shin			
Calf muscle			

Table C.1 lists the body locations that can be subjected to the contact hazards presented. According to the reports from the clinical studies (conducted by University Mainz[12] and Fraunhofer IFF)[10,11] that have ascertained the biomechanical limits, the pressure limits have been measured with a resolution of 25 DPI (see Annex B.2).

C.3 Measurement setup

The PFMD available for testing all contact hazards is equipped with sensitive film for peak pressure measurement (see 5.4.3). The film delivered pressure images with a resolution of 200 DPI.

Setup for contact hazard 1

The curvature radii on the surface of the robot gripper are smaller than those on the surface of the workpiece. The PFMD is therefore placed on the conveyer with the impact side towards the robot gripper. Figure C.2 (2) illustrates this situation.

Setup for contact hazard 2

The small gaps between the workpiece and the gripper fingers require the use of a PFMD that is especially designed for small spaces, as illustrated in Figure C.3 (2). Irrespective of the size of the PFMD, a support structure should be used to keep it in position during the test. Holding it by hand is not recommended to avoid the hand or fingers of the tester to get pinched.

Setup for contact hazard 3

The available PFMD is not designed to measure unconstrained contacts (see 6.3) and should be affixed to a rigid structure. This is achieved by placing the PFMD on a tripod and stabilizing it in direction of the impact force by using a metal beam that transfers the force to a rigid pillar. Figure C.4 (2) illustrates this situation (tripod is not visible).

C.4 Test conditions

For the test, the robot was switched on an hour ago and all systems are fully warmed up. All technical measures that were not implemented as a safety function have been switched off or removed (see 7.1). The robot control unit does not display any error messages or warnings.

During the tests, the robot will execute the same program as it will later run during productive operation. The workpieces that will be used in the tests are same as in the application. Additionally, the tests will be carried out in the same environment in which the robot will be deployed.

C.5 Test execution

Each combination of a contact hazard and possibly affected body location is tested twelve times ($N = 12$). The stepwise procedure described in 7.3 was followed.

C.6 Analysis of the measurement values

The following illustrates an analysis of the measurement data received from tests in which contact hazard 3 was tested with a PFMD that was configured to the parameters for *sternum*. The measurement data from the other tests will be analyzed in the same way (not presented here).

Analysis of the measurement data for contact hazard 3

Table C.2 lists maximum transient forces and pressures ($N = 12$) measured by a fixed PFMD. Prior to the analysis, all force signals have been filtered as described in 5.4.2. The resolution of all pressure images was reduced from 200 DPI (16 data points per mm^2) to 25 DPI (one data point per mm^2) as recommended in 5.4.3 (see Figure C.5).
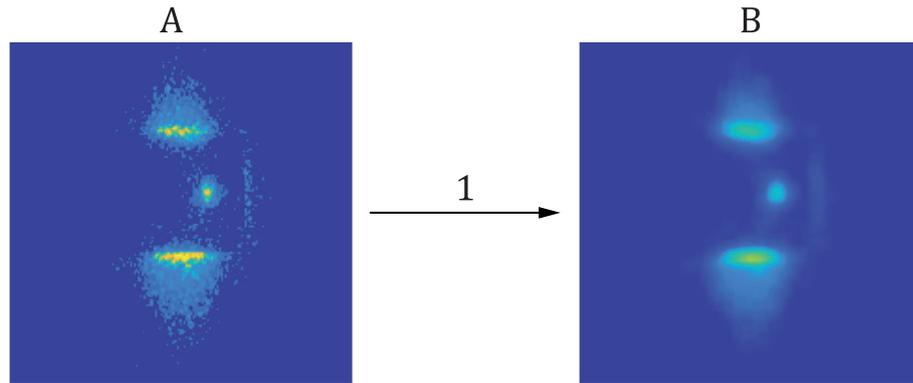
Key

A   pressure image @ 200 dpi

B   pressure image @ 25 dpi

1   averaging filter

Figure C.5 — Downscaling of the pressure images resolution (from 200 DPI to 25 DPI)

According to Table 2 in 7.4, four outliers (two of the highest and two of the lowest measurement values) were discarded.

Table C.2 — Measured force values from contact hazard 3 tests recorded with a PFMD that replicates the sternum (*not relevant since impact does not have a quasi-static phase)

M	Max. force [N]		Comment
	Transient	Quasi-static*	
1	321	-	
2	324	-	
3	309	-	
4	320	-	
5	318	-	
6	328	-	
7	334	-	Discard
8	336	-	Discard
9	309	-	
10	321	-	
11	304	-	Discard
12	306	-	Discard

Table C.3 — Measured pressure values from contact hazard 3 tests recorded with a PFMD that replicates the sternum (*not relevant since impact does not have a quasi-static phase)

M	Max. pressure [N/cm^2]		Comment
	Transient	Quasi-static*	
1	80	-	
2	92	-	Discard
3	74	-	Discard
4	83	-	
5	78	-	
6	89	-	

Table C.3 *(continued)*

M	Max. pressure [N/cm^2]		Comment
	Transient	**Quasi-static***	
7	71	-	Discard
8	80	-	
9	84	-	
10	89	-	
11	95	-	Discard
12	81	-	

Next, the conversion technique is applied (see 6.3.3) to obtain the projected maximum transient forces $\tilde{F}_{TR}$ and projected maximum transient pressures $\tilde{p}_{TR}$ that would have been measured with a movable PFMD. In this example, the triangle method is applied to estimate the momentum I_R transferred by the robot. The safety functions of the robot limit its speed to $v_R = 0,45\,\text{m/s}$. This speed and the momentum I_R can then be used to estimate the apparent robot mass m_R. According to Table A.3 in ISO/TS 15066:2016, the effective mass for body location *sternum* is $m_H \approx 40\,\text{kg}$. Both, the effective robot mass m_R and effective human body mass m_H lead to the scaling factor S that finally converts the maximum transient forces F_{TR} and pressures p_{TR} measured to $\tilde{F}_{TR}$ and $\tilde{p}_{TR}$. Figure C.6 displays the result from the conversion technique for the first measurement (M1). Table C.2 and C.3 list the force and pressure values from all measurements.
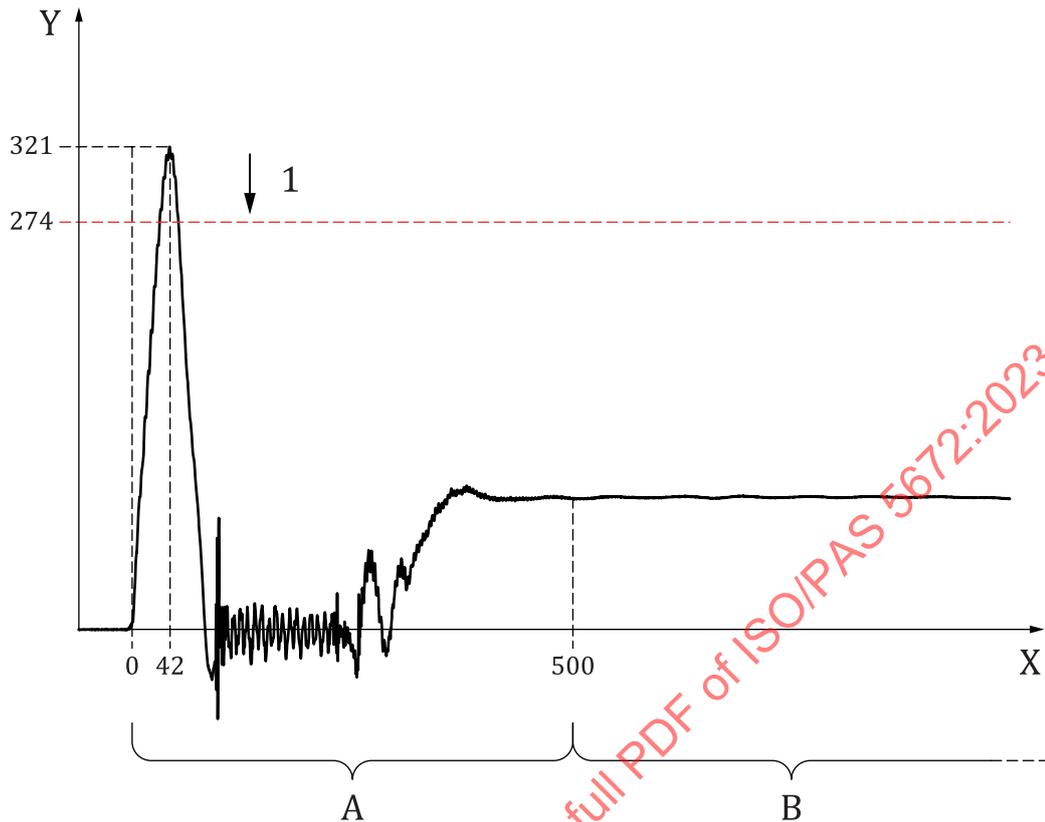
Key

X   time [ms]
Y   force [N]
1   conversion technique
A   transient contact phase
B   quasi-static contact phase

Figure C.6 — Force signal measured in contact hazard 3 tests with a fixed PFMD (M1 in Table C.2)

Table C.4 — Maximum transient forces F_{TR} and pressures p_{TR} after applying conversion technique (*discarded values)

M	F_{TR} [N]	t_{TR} [ms]	I_R [Ns]	v_R [m/s]	m_R [kg]	S [-]	$\tilde{F}_{TR}$ [N]	$\tilde{p}_{TR}$ [N/cm^2]
1	321	42	6,74		15,0	0,85	274	68
2	324	42	6,73		15,0	0,85	276	*
3	309	44	6,79		15,1	0,85	263	*
4	320	42	6,75		15,0	0,85	273	71
5	318	42	6,75		15,0	0,85	271	67
6	328	41	6,79		15,1	0,85	279	76
7	334	40	6,71	0,45	14,9	0,85	*	*
8	336	41	6,76		15,0	0,85	*	68
9	309	44	6,77		15,0	0,85	263	72
10	321	42	6,73		15,0	0,85	274	76
11	304	44	6,75		15,0	0,85	*	*
12	306	44	6,70		14,9	0,85	*	69

From the projected maximum transient forces $\tilde{F}_{TR}$ and pressures $\tilde{p}_{TR}$ listed in Table C.4, the relative standard deviation $\tilde{\sigma}$ is calculated and then compared to the thresholds for force (5 %) and pressure (10 %; see 7.4). If the relative standard deviation values $\tilde{\sigma}$ do not exceed their thresholds, the measurement setup seems to be properly designed (criterion 1; which is the case here, see Table C.5).

Table C.5 — Comparison of the relative standard deviations $\tilde{\sigma}$ for force and pressure to their thresholds (*not relevant since impact does not have a quasi-static phase)

Criteria 1 (quality indicator for the measurement setup)				
Contact phase	Relative standard deviation for	$\tilde{\sigma}$ [%]	Threshold	Measurement Setup
Transient	Force [N]	2,1	5	OK
	Pressure [N/cm^2]	5,0	10	OK
Quasi-static*	Force [N]	-	5	N/A
	Pressure [N/cm^2]	-	10	N/A

Afterward, the means μ are calculated from the measurement values and then compared to the biomechanical force and pressure limits. The test is considered passed if the mean values μ for force and pressure do not exceed their limits (criterion 2; which is the case here, see Table C.6).

Table C.6 — Comparison of the means μ for force and pressure to the biomechanical limits (*not relevant since impact does not have a quasi-static phase)

Criteria 2 (comparison of sample means with the biomechanical limits for the body location tested)				
Contact phase	Mean for	μ [%]	Limit	Test
Transient	Force [N]	272	280	passed
	Pressure [N/cm^2]	71	240	passed
Quasi-static*	Force [N]	-	140	N/A
	Pressure [N/cm^2]	-	120	N/A