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

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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, Annex N, robot applications and robot cells integration (based on RIA TR R15.806:2018) or ISO/TS 15066:2016.

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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 10218-2¹⁾, *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

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

3.3

biomechanical response

behavior 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:

- 1) 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).
- 2) 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).

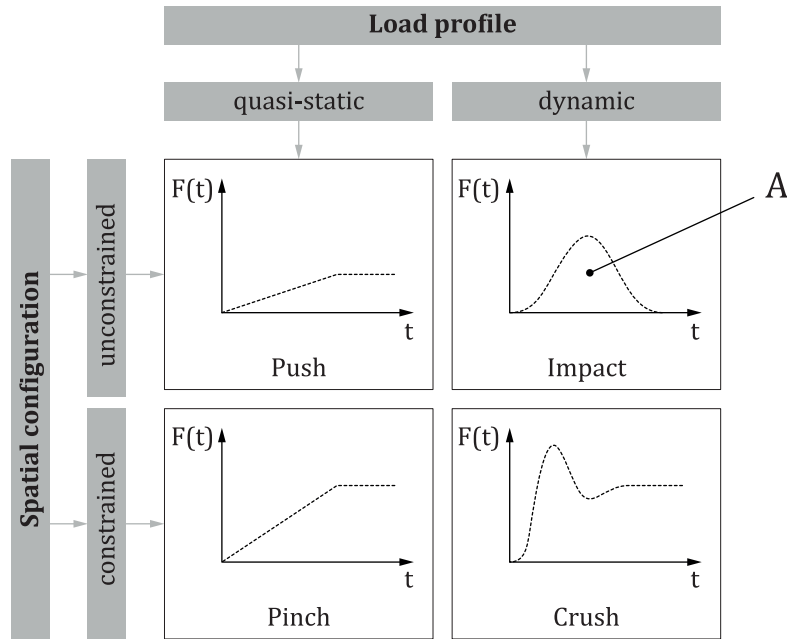
NOTE 1 A condition for unconstrained spatial configurations is the free distance to the next fixed object or obstacle which is at least 500 mm. More precise distance values can be found in ISO 13854:2017.

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)

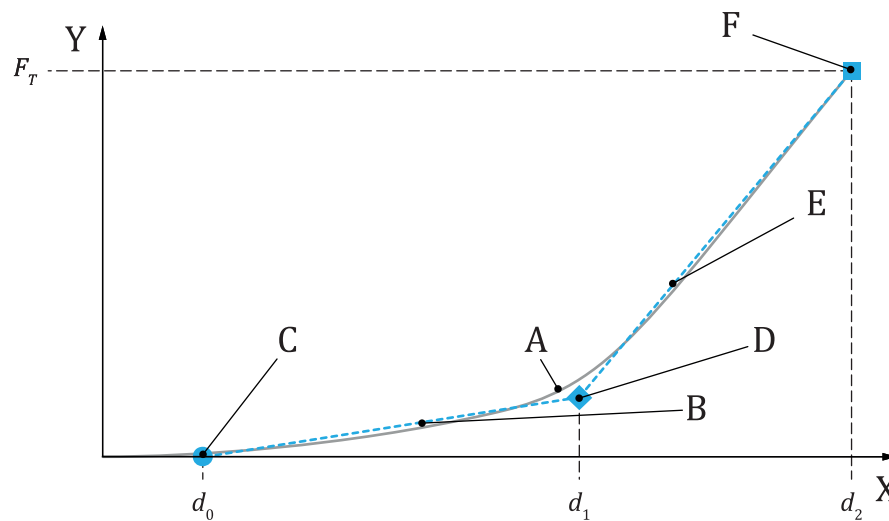
Contacts can also occur with structures in the environment of the robot. Especially before testing pinch or crush points, it should be identified if the contact surface with the smallest curvature radii is on the robot or on the obstacle in the environment of the robot. The pressure shall be measured 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	B	first line that approximates the first part of a response curve (i.e., from d_0 to d_1)
Y	contact force applied to a human body part	C	point (d_0) at which the first line intersects with the deformation axis
F_T	force limit for transient contact phase	D	point (d_1) at which both lines intersect
A	response curve as derived from the same biomechanical data that were used to determine the transient force limit	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 [equation \(1\)](#) 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 ≥ 100 Hz and at a resolution of ≤ 1 N and $\leq 0,1$ 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.

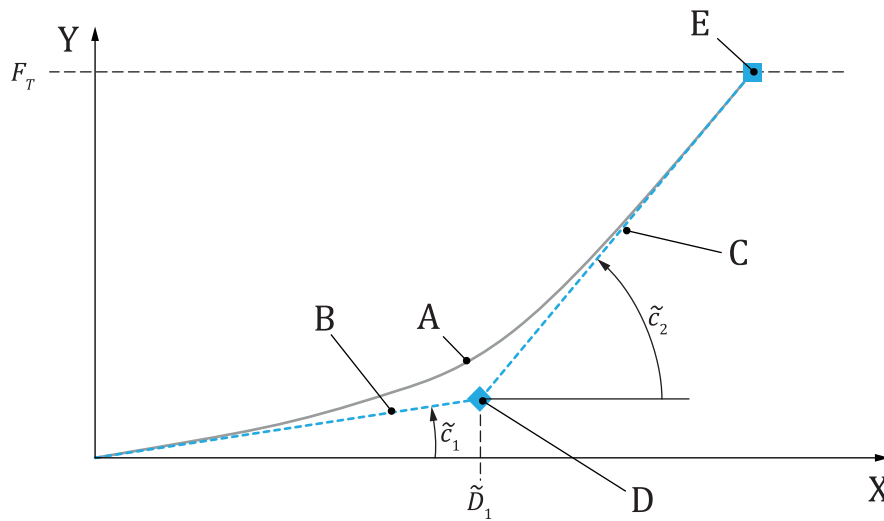
Once the response curve is measured accordingly, it shall be approximated by two lines. The first line shall approximate the first of the response curve (from d_0 to d_1) and the second line the second part (from d_1 to d_2). For the approximation of the first part, the starting slope (\tilde{c}_1) shall 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:

- (1) $\tilde{D}_1 \leq D_1$ (i.e., \tilde{D}_1 shall not exceed D_1 from the reference response curve)
- (2) $\tilde{c}_1 \times \tilde{D}_1 \leq c_1 \times D_1$ (i.e., the product of \tilde{c}_1 and \tilde{D}_1 shall not exceed the product of c_1 and D_1)
- (3) $\tilde{c}_2 \geq 0,75 \times c_2$ (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 (1) and (2), 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 (e.g., see ISO/FDIS 10218-2:2020 Annex N).

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 6487:2015. An exemplary filter implementation can be found in ISO 6487, Annex A. A CFC 60 filter will have only an effect on pressure signals if these signals were sampled with frequencies of ≥ 600 Hz.