TECHNICAL
REPORT

ISO/TR
23482-1

First edition
2020-02

Robotics — Application of ISO 13482 —

Part 1:
Safety-related test methods

Robotique — Application de l'ISO 13482 —

Partie 1: Méthodes d'essai liées à la sécurité

Reference number
ISO/TR 23482-1:2020(E)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

Contents

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 documents 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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

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

This document describes test methods used to verify safety criteria of personal care robots. This document is intended to facilitate ISO 13482, which summarizes the safety requirements of personal care robots. This document describes test methods which are guidelines to verify compliance to the requirements of ISO 13482. Together with the other verification and validation methods described in ISO 13482, they are selectively applicable according to the robot design and usage.

At the time of publication, the test methods described in this document have not been implemented or evaluated broadly. Due to a lack of test facilities worldwide able to conduct such tests, it has not been possible to conduct formal round robin tests. Users of this document are therefore advised to apply the tests with care.

Robotics — Application of ISO 13482 —

Part 1:
Safety-related test methods

1 Scope

This document describes methods that can be used to test personal care robots in terms of safety requirements defined in ISO 13482. The target robots of this document are identical to those of ISO 13482.

The manufacturer determines the required tests and appropriate testing parameters based on a risk assessment of the robot's design and usage. This risk assessment can determine that tests and test parameters other than those contained in this document are acceptable.

Not all test methods are applicable to all robot types. Test methods labelled "universal" are applicable to all personal care robots. For other tests, the heading states for which robot types the test can be applied (e.g. "for wearable robot" or "for mobile robot").

Some test methods can be replaced by using other applicable standards, even if they are not listed in this document.

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 13482:2014, *Robots and robotic devices — Safety requirements for personal care robots*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13482:2014 and the following apply.

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

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

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

3.1
autonomy
ability to perform intended tasks based on current state and sensing, without human intervention

[SOURCE: ISO 8373:2012, 2.2]

3.2

operator

person designated to make parameter and program changes, and to start, monitor, and stop the intended operation of the personal care robot

[SOURCE: ISO 8373:2012, 2.17, modified — The words “to make parameter and program changes, and” have been added, and the words “of a robot or robot system” have been replaced with “of the personal care robot”.]

3.3

electro-sensitive protective equipment

ESPE

assembly of devices and/or components working together for protective tripping or presence-sensing purposes and comprising at a minimum

— a sensing device,

— controlling/monitoring devices,

— output signal switching devices and/or a safety-related data interface

Note 1 to entry: The safety-related control system associated with the ESPE, or the ESPE itself, can further include a secondary switching device, muting functions, stopping performance monitor, etc.

Note 2 to entry: A safety-related communication interface can be integrated in the same enclosure as the ESPE.

[SOURCE: ISO 13855:2010, 3.1.4, modified — The words “and/or a safety-related data interface” have been added, and the original Note has been replaced with Notes 1 and 2 to entry.]

4 Test conditions

4.1 General

This clause describes typical operating conditions for indoor use. Where applicable, tests are carried out under the worst-case operating conditions.

Unless specified differently, the robot is completely assembled, fully charged, and operational based on the manufacturer’s specification for all tests. All self-diagnostic tests are satisfactorily completed.

4.2 Environmental conditions

The following environmental conditions apply during all tests:

— ambient temperature: 10 °C to 30 °C;

— relative humidity: 0 % to 80 %.

If the environmental conditions specified by the manufacturer are outside the given conditions, this is declared within the test report.

4.3 Test travel surface

The coefficient of friction for test travel surface is between 0,75 and 1,0 (see ISO 7176-13) unless specified otherwise by the manufacturer.

4.4 Safety of persons involved in testing

4.4.1 General

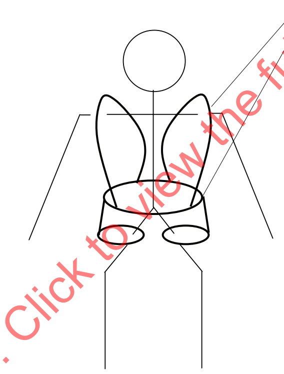
During the preparation and conduction of verification and validation tests, the persons involved in testing are protected as far as possible from any risk originating from the robot and the test apparatus. Special attention is paid when tests provoke hazardous situations such as collisions and instability.

Where possible, tests are conducted remotely with no person near the robot. Human presence and intervention are simulated where applicable by using dummies.

Where a human tester cannot be replaced by a dummy or by an automated device, a risk assessment is performed to identify the hazards that can occur during the test. Where necessary, test persons are advised to wear protective equipment to lower risks from collision and falling.

4.4.2 Safety harness

The test operator of a person carrier robot and physical assistant robot is exposed to hazards of falling down. Therefore, in addition to conventional safety apparatus such as helmets, kneepads and elbow pads, the test operator is secured by a safety harness suspended from a supporting structure over the test travel surface if the expected risk is not tolerable (Figure 1).



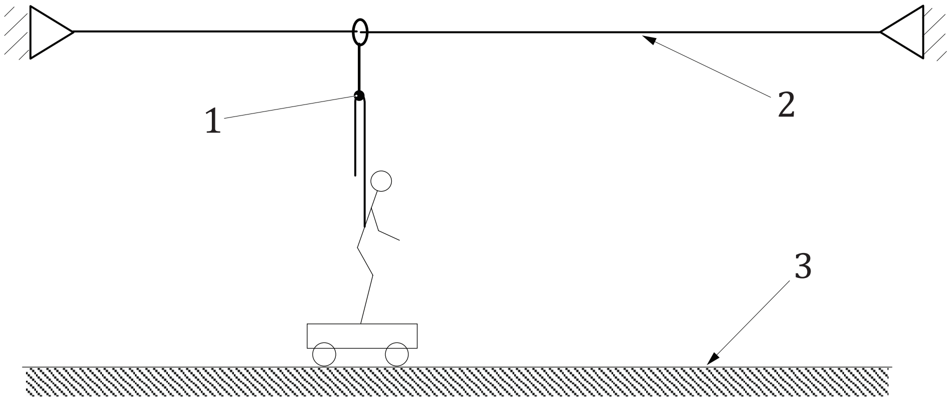
Key

1 safety jacket

Figure 1 — Example of safety harness

The safety harness has sufficient reliability, equivalent to harnesses used for fall protection. The cable connected to the supporting structure has sufficient elasticity. Additionally, its length is adjusted to prevent the test operator from falling to the travel surface. The supporting upper structure can be a rigid rail or a flexible wire on which a pulley block runs. The pulley block can be powered to follow the test operator's movement. (Figure 2)

NOTE ISO 16024 specifies design and performance of personal protective equipment for protection against falls from a height.



Key

1 movement device

2 guide rail

3 test travel surface

Figure 2 — Example of supporting upper structure and pulley block

5 Selection of test sample

The sample item, either a robot system or a robot component, is representative of the target design.

NOTE 1 If the sample item is broken, it is repaired or replaced between test sequences.

NOTE 2 Some functions of the sample can be intentionally disabled or tuned when the test demands irregular conditions, e.g. an obstacle detection sensor in a mobile-type robot is disconnected in a collision impact test.

6 Test of physical hazard characteristics (universal)

6.1 Voltage at user-accessible parts

6.1.1 Principle

This test measures voltages supplied at user-accessible parts in order to verify designs protecting against “contact with live parts of the robot” (see ISO 13482:2014, 5.3.1.1).

This test is applicable to all robots that are operated by electrical power.

The test consists of two steps:

a) examining accessible parts, and

b) measuring the supplied voltage in the accessible parts.

The test uses three different apparatuses:

- test fingers,
- a load cell or force limiter attached to the test fingers, and
- a voltmeter.

This test is conducted once for a new robot and once for a test sample that has been in operation for a number of use cycles representative for the lifetime of the robot. The used test sample is carefully examined for signs of wear, which can have one of the following effects:

- breaking of cables that lead to parts becoming live,
- breaking of guards that lead to more parts becoming accessible.

Where other tests described in this document lead to severe damage of the robot or some of its parts (e.g. collision tests), it is advisable to repeat this test if new hazards might have formed then.

6.1.2 Apparatus

a) Test finger (test probe code according to IEC 61032)

A jointed type probe (probe code B), an unjointed type probe (probe code 11) and a small-diameter jointed type probe if the test is necessary with regards to children (probe code 18 or 19).

b) Load cell or customized jig tool

A load cell able to measure compression force or a jig tool, such as a limiter, that can be removed when applying a specified compression force.

c) Voltmeter

6.1.3 Procedure

a) Survey of accessible parts

The accessible parts of conductive areas are identified with the following procedure. These are user-accessible parts on the robot. They can be accessible during normal use or during maintenance and inspection, etc. (The scope of maintenance and inspection work by the user is specified by the manufacturer in the user manual.)

1) Opening covers and doors that can be opened without tools, keys, etc.

2) Visual inspection of the accessible area

3) Identification of accessibility by a jointed test finger. The test finger is applied with a force not exceeding 1 N to openings of the robot. Through openings, the test finger is applied to any depth that the test finger will permit and is rotated or angled before, during and after insertion to any position. If the opening does not allow the entry of the test finger, the force on the test finger in the straight position is increased to 20 N. If the test finger then enters the opening, the test is repeated with the test finger in the angled position.

Where necessary, the unjointed test finger is used and a force of 10 N ± 1 N or a higher, if specified by the manufacturer, is applied.

b) Measuring electrical potential

A voltage between an accessible part judged in a) and a reference point is measured under normal operating condition of the robot with power on (during operation, if necessary). The reference point of electrical potential is the protective earthing point or an equipotential point if the robot is equipped with a protective earthing system, or otherwise the functional earthing point or an equipotential point or the potential point of the power source’s negative terminal. At locations of electric potential, the standard resistance of 2 kΩ or, if operation under high humidity is anticipated, a resistance of 500 Ω is applied between the reference points. The electrical current through this resistance or the voltage is measured.

If the operational mode influences which robot parts become live, the measurement is performed for each potentially harmful operational mode.

c) Report of test data

Results are recorded through with the diagram or photo of the tested area.

6.2 Acoustic noise

6.2.1 Principle

This test measures the maximum sound level of acoustic noise that is transmitted to a human passing by at a 1 m distance, as well as noise transmitted to a person onboard/user wearing the robot, in order to verify designs protecting against "hazardous noise" (see ISO 13482:2014, 5.7.1.1).

This test is applicable to all robots generating sound.

The test consists of three steps:

a) programming a travel pattern,

b) measuring pass-by noise, and

c) measuring noise while riding/wearing (if applicable) using sound level meters.

The measurement employs A-weighted sound pressure level. Allowable background noise is not necessarily eliminated to perform the measurement.

6.2.2 Apparatus

a) Test travel surface

Test travel surface is composed of measurement section of a 10 m straight-line preceded by an acceleration section of enough length for accelerating the target robot to its rated speed. The travel surface is chosen to simulate the worst-case travel environment for the robot. Background noise on the travel surface is insulated to be at least 10 dB lower than the measured noise level (e.g., compliance with Grade 3 of ISO 11202:2010, Annex B). Secondary noise reflected from objects around the travel surface is sufficiently supressed.

b) Precision noise meter (Class I) (IEC 61672-1) for pass-by noise measurement

The test is carried out by positioning microphones as described in 6.2.3 b). The noise meter has microphone(s) connected to frequency analysis-capable data logger.

c) Precision noise meter (Class 1) for measuring noise heard by the person on board

The noise meter is portable in order to be carried by the robot during the test. It is equipped with a windshield and is fixed where the ear of the person on board/user wearing the robot is located during normal operation.

6.2.3 Procedure

a) Preparation of robot travel pattern

Two robot travel patterns to sample sound level are as follows:

1) tracing straight-line path keeping rated speed during measurement section, and

2) tracing straight-line path, starting with the rated speed at beginning of the measurement section, then performing the maximum deceleration to stop at the midway point of the measurement section for 1 s, and finally performing the maximum acceleration to return to the rated speed until the end of the measurement section.

The robot is programmed to perform these patterns, when testing a mobile servant robot. If the robot cannot be programmed, it is prepared to be manually controlled. A test person onboard or a test person wearing the robot is instructed to manoeuvre the robot to perform these patterns, when testing a person carrier robot or a physical assistant robot. In the latter case, the rated speed is considered to be the fastest walking speed specified by the manufacturer.

During the measurement, it is checked whether the specified test speed is achieved.

b) Installation of microphones for the noise meter for pass-by noise measurement

Four microphones for the pass-by noise meter are placed on the centre of the measurement section of the test travel surface, with two microphones at the height of 0,2 m above the travel surface, with interval of 1 m. The remaining two microphones are fixed at a height of 1,6 m at an interval of 1 m. All microphones are directed at the right angles to the travel path of the robot, positioned on a vertical plane 0,5 m away from the closest point of the robot surface.

c) Measurement of pass-by noise

The target robot performs the two travel patterns a) 1) and a) 2) a minimum of four times each. The sound pressure level with fast A-weighting measured by the four microphones is recorded during the test. The pass-by noise for each repeated measurement is determined by averaging the maximum overall values sampled by the two microphones at each height level from the travel surface. Pass-by noise for each travel pattern is calculated as the average value from all repeated measurements. The maximum value among the pass-by noise for the two travel patterns and the two microphone heights is recorded as the test result.

d) Measurement of noise heard by the person on board/user wearing the robot

The target robot performs the two travel patterns a) 1) and a) 2) a minimum of four times each. The sound pressure level with fast A-weighting is measured by a microphone fixed where the ear of the person on board/user wearing the robot is located during normal operation for this test. The noise heard by the person on board/user wearing the robot for each pattern is calculated as the average of the maximum overall value of recorded sound pressure. The higher noise of the two travel patterns is recorded as the test result.

NOTE The sound pressure level is averaged by the following formula.

$$L_m = 10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{L_i/10}\right)$$

where

L_m is the average of the sound pressure level (dB);

L_i is the sound pressure level measured as the *i*-th data (dB);

n is the number of the data.

6.2.4 Pass/fail criteria

Reference can be made to Clause A.2 to define pass/fail criteria for the test, and the data described in it.

6.3 Surface temperature

6.3.1 Principle

This test measures surface temperatures of the robot in order to verify designs protecting against "extreme temperature" (see ISO 13482:2014,5.7.4.1).

This test is applicable to all robots.

The test procedure consists of three steps:

a) examining accessible parts,

b) operating the robot at the maximum rated-power, and

c) measuring the surface temperatures of the parts using a thermography camera or thermocouple.

6.3.2 Apparatus

a) Test finger (test probe code according to IEC 61032)

A jointed type probe (probe code B), an unjointed type probe (probe code 11) and small-diameter jointed type if the test is necessary with regards to children (probe code 18 or 19).

b) Temperature measurement device

- Thermography camera is used if the highest or lowest temperature point is not known in advance or multiple points are measured in a short time.
- If the area to be measured is small, a spot thermometer can be used instead.

A thermocouple can be used if the measurement points are identified in advance. A thinner gauge is preferred to avoid heat transferring via thermocouple.

6.3.3 Procedure

To determine the maximum temperatures, tests need to be carried out at the highest allowable environment temperature as specified by the manufacturer. If in addition low temperatures are of interest, tests need to be repeated at the lowest allowable environmental temperature.

a) Survey of accessible parts

The user-accessible parts of the target robot in normal use and during maintenance, or inspection, etc., by the user, are identified with the following procedure. (The scope of normal use, maintenance, inspection, etc., by the user is specified by the manufacturer in the user manual.)

1) Opening covers and doors that can be opened without tools, keys, etc.

2) Visual inspection for the accessible area.

3) Judgement of accessibility by a jointed test finger.

Where necessary, an unjointed test finger is used to apply either the manufacturer specified pressure or 10 N ± 1 N.

b) Continuous operation of the target robot under load

The test is performed under the worst-case expected ventilation conditions. Detachable covers are attached to the robot and doors are closed. Where load or passengers on the robot are likely to interfere with heat dissipation, they are present or otherwise an equivalent condition is achieved. The worst-case ventilation conditions are chosen for testing hazardous low temperatures.

The following settings and operation are executed, depending on the type of the robot.

1) Mobile servant robot or person carrier robot: Continuous operation with the maximum rated load, until one of the following conditions is satisfied:

   - Reaching the designated time length of continuous operation;
   - Reaching equilibrium after a rise or drop in temperature;
   - The fully charged battery on the robot is spent.

   2) Physical assistant robot: Movements in normal use by the user specified by the manufacturer are reproduced without any special attachments and the temperature reaches thermal equilibrium, or the robot is continuously operated until the fully charged battery on the robot is spent.

c) Surface temperature measurement

   Temperature is measured on the highest/lowest temperature surface point in accessible parts. Measurement is done while thermal equilibrium condition continues, or otherwise immediately after the robot ceases moving. Especially for enclosed parts, measuring begins within 1s after opening the cover, door, etc. Measurement reading is stable for a short time before the temperature significantly changes. When using a thermography camera, continuous sampling is finished within 5 s.

   Temperature is continuously monitored after turning the robot's power off, if the robot becomes hotter after stopping its active ventilation.

6.3.4 Pass/fail criteria

The data described in Clause A.3 can be referred to for defining pass/fail criteria for the test.

7 Test of physical hazard characteristics (for mobile robot)

7.1 Injury parameters in collision

7.1.1 Principle

This test measures forces, displacements, velocities and accelerations in human dummies, representing persons onboard and pedestrians, during a collision of robots in order to validate designs protecting against the risks caused by "collision with safety-related obstacles" (see ISO 13482:2014, 5.10.8). Pressure and other related physical quantities can be measured.

NOTE Pain thresholds in ISO/TS 15066:2016, Clause A.3 can be applied.

This test is applicable to all robots that are mobile.

This test consists of three steps:

a) soak and set-up,

b) collision and measurement, and

c) data processing.

This test uses three apparatuses:

- crush barrier,
- a travel surface, and
- test dummies.

One dummy is hit by the robot and, if applicable, another dummy is mounted on the robot as a passenger.

For the test, the highest expectable hazardous condition for a collision between robot and pedestrian needs to be specified in a risk assessment.

7.1.2 Apparatus

a) Crush barrier

The barrier is a wall structured to resist against a collision with the robot, maintaining a vertical plane against the path of the robot. The collision surface is rigid enough to ignore deformation by collision and is fixed to the floor rigidly enough that the movement during collision is negligibly small.

b) Travel surface

The path is horizontal and flat, with adequate length and width for the robot to reach its maximum speed. The coefficient of friction for the part of the robot that contacts to the travel surface at collision is based on ISO 7176-13.

c) Test dummy of human body

Biomechanical features (dimension, weight, etc.) of the human body are reflected as closely as possible such that forces, pressures, moments, displacements, speeds, accelerations and other related physical quantities necessary for estimating the harm can be measured correctly.

NOTE The type of dummy is chosen according to the anticipated size and weight of humans in the designated use environment. For example, the following test dummy can be used in this test.

— Passenger dummy: Hybrid III test dummy specified in US Code of Federal Regulations, Title 49, Part 572, Subpart E, which represents the 50th percentile of adult males. Force transducers are added to the arms if necessary.

— Pedestrian dummy: For an adult, Hybrid III test dummy specified in US Code of Federal Regulations, Title 49, Part 572, Subpart O, which represents the 5th percentile of adult females. Force transducers are added to the arms if necessary. For children, Q6 test dummy specified in UN Regulation No. 44 Annex 8.

The test dummy wears shoes and can also wear cotton shirt and trousers. The rigidity of the joints of the test dummy limbs are adjusted to be able to maintain its own weight when the limbs are positioned horizontally.

The Hybrid III test dummies were developed for high-energy collisions. Testing equipment with the biomechanical properties described in ISO/TS 15066 can be considered in conjunction with test methods.

7.1.3 Procedure

a) The dummy is soaked in the specified room temperature to stabilize its temperature at which the biofidelity of the dummy is obtained.

b) The test is conducted under normal robot operation conditions with the power turned on, or the robot's normal operation is simulated by external driving forces with the robot's power turned off.

c) The load on the robot is set at maximum. In case of a person carrier robot, a dummy is loaded according to the mounting method specified by the manufacturer. For a robot carrying loads, load as specified by the manufacturer.

d) The robot is accelerated to the specified speed on the acceleration section and it collides with the dummy simulating a pedestrian. The collision requirements are as follows.

  1) Tests are conducted a minimum of four times under each for the following conditions: the first condition where there is no barrier to constrain the movement of the dummy during and after the collision, other than the travel surface and the robot; the second condition where the dummy is contact with a barrier prior to the collision; and the third condition where the unconstrained dummy is pressed against the barrier during and/or after the collision.

  2) The test dummy to simulate the pedestrian is placed upright at the centre of the robot's travel path and needs to maintain an upright position until immediately before collision with the robot. Tests are conducted for each direction of the dummy at collision, i.e. collision while facing the robot, collision to the back of the dummy and collision from the side of the dummy.

The movement of the dummy after collision is not to be restrained by anything other than the barrier, the travel surface and the robot.

3) The general travel direction of the robot is the forward direction. For robots able to move in directions other than forward, however, the test is conducted for such directions, especially if there is a collision direction in which the expected severity of injury of the pedestrian is identical to or more than in the forward direction. Special attention is paid to the robot's structure and shape, travel speed and person onboard load conditions.

e) If the robot has a person onboard, the test is conducted for collision with barriers. The robot accelerates to the specified speed on the acceleration section and to collide with the barrier. For robots able to move in directions other than forward, this test is conducted for such directions, if there is a collision direction in which the load on the person onboard is identical to or more than the forward direction. Special attention is paid to the robot's structure and shape, travel speed and person onboard load condition.

f) Mechanical parameters on each part of the dummy in collision are measured in accordance with SAE J211-1. The physical quantities are measured are as follows:

   1) acceleration of the head (longitudinal, lateral and vertical directions);

   2) angular velocity of the head (about the centre of gravity);

   3) axial force of the neck;

   4) bending moment of the neck;

   5) displacement of the chest;

   6) load on the pelvis;

   7) load on the leg; and

   8) load on the arm.

g) It is checked if the specified test speed is achieved.

h) To prevent the effects of the hysteresis of the dummy, time intervals between each test specified by the dummy manufacturer need to be applied.

7.1.4 Pass/fail criteria

The data described in Clause A.4 can be referred to for defining pass/fail criteria for this test.

7.2 Test of force control for intended and unintended contact with a robot

7.2.1 Principle

This test measures the contact force/impulse during intended/unintended physical interaction between a safety-related obstacle and the robot, which is specified through risk assessment in order to validate that the amount of force/impulse does not exceed the value appropriately chosen by safety verification. The safety verification data can be provided either by ISO/TS 15066 or by some numeric values from other sources including the results of ongoing activity on safety data for human-machine interactions, if appropriate (see ISO 13482:2014, 4.3 and 5.10.9.1).

This test is applicable for all personal care robots that use force control for risk reduction.

7.2.2 Apparatus

a) Contact piece

The contact piece that represents a safety-related obstacle and simulates the compliance of a safety-related obstacle (e.g. in case of human body, a certain spring constant specified in ISO/TS 15066:2016, Annex A).

b) Force transducer

The transducer to measure the contact force acts on the contact piece. It has a response fast enough to measure the impulse during the contact.

c) Pressure sensor

A sensor to measure the pressure distribution over the contact area. It is used if the contact pressure is measured, and it has a response fast enough to measure the impulse during the contact.

7.2.3 Procedure

a) The contact piece is fixed on a stiff wall. The pressure sensor is fixed either on the contact surface of the test piece or on the robot.

b) The force control of the robot is activated.

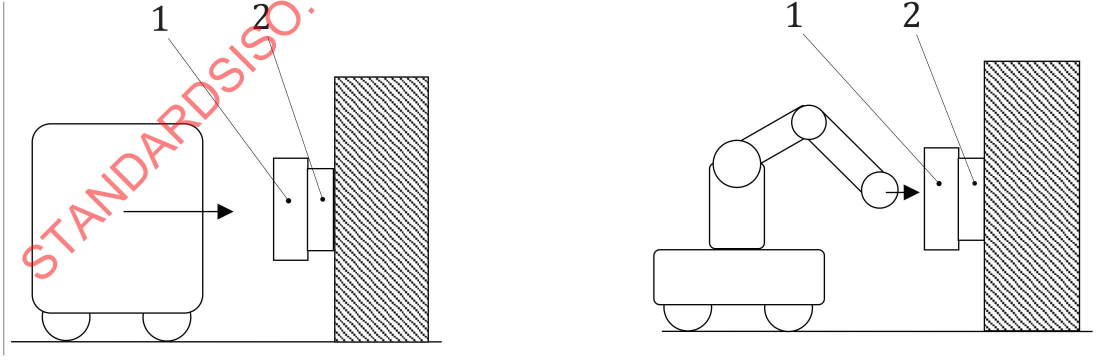
c) For the force control of mobile robot travelling, the robot is put along the line toward the contact piece with enough distance for the robot to accelerate to its maximum speed, as shown in Figure 3 a). In case of the force control for a moving part of the robot, the robot is placed in front of the contact piece as in Figure 3 b).

d) For the force control of a moving part of the robot, the part is moved against the contact piece, as shown in Figure 3 b)

e) For the force control for mobile robot travelling, the robot contacts the contact piece. For the force control of a moving part of the robot, the part to contact the contact piece.

f) The contact force is recorded.

g) The steps c) to f) are repeated a minimum of four times.



a) Test of mobile robot **b) Test of moving part**

Key

1 contact piece

2 force transducer

Figure 3 — Test of force control

7.2.4 Pass/fail criteria

The data described in Clause A.4 can be referred to for defining pass/fail criteria for this test.

8 Test of physical hazard characteristics (for restraint type physical assistant robot)

8.1 Principle

This test measures interactive forces, pressures and displacements/velocities, generated at the contact surfaces between restraint type physical assistant robots and human skin, to ensure that “physical stress or strain to the user” is minimized during normal operation (see ISO 13482:2014, 5.9.2.1).

This test is applicable to robots, which have one or more contact surfaces to be attached to the human body and there is a probability of stress concentration on these skin areas.

The test procedure consists of the following steps:

a) The contact states and pattern of the maximum load are defined on the human body. During this test the robot is worn and the operator follows predetermined periodical motion patterns.

b) A test piece simulating human hypodermis is prepared. This test piece is placed under the cuffs of the physical assistant robot such as upper/lower extremities, waist, etc., a porcine skin piece is fixed, if necessary, between the surfaces of the cuff and the simulating test piece.

c) If necessary, replicate the pattern of the maximum/average load exerted on the simulating test piece in the same contact states as those defined in step a).

An overview of the above test procedure is illustrated in Figure 4, where test flow is classified into two cases:

- measuring forces/pressures if the stress concentration areas can be identified and can be monitored;
- observing damages on the simulating test piece in b) if the stress concentration cannot be well monitored.

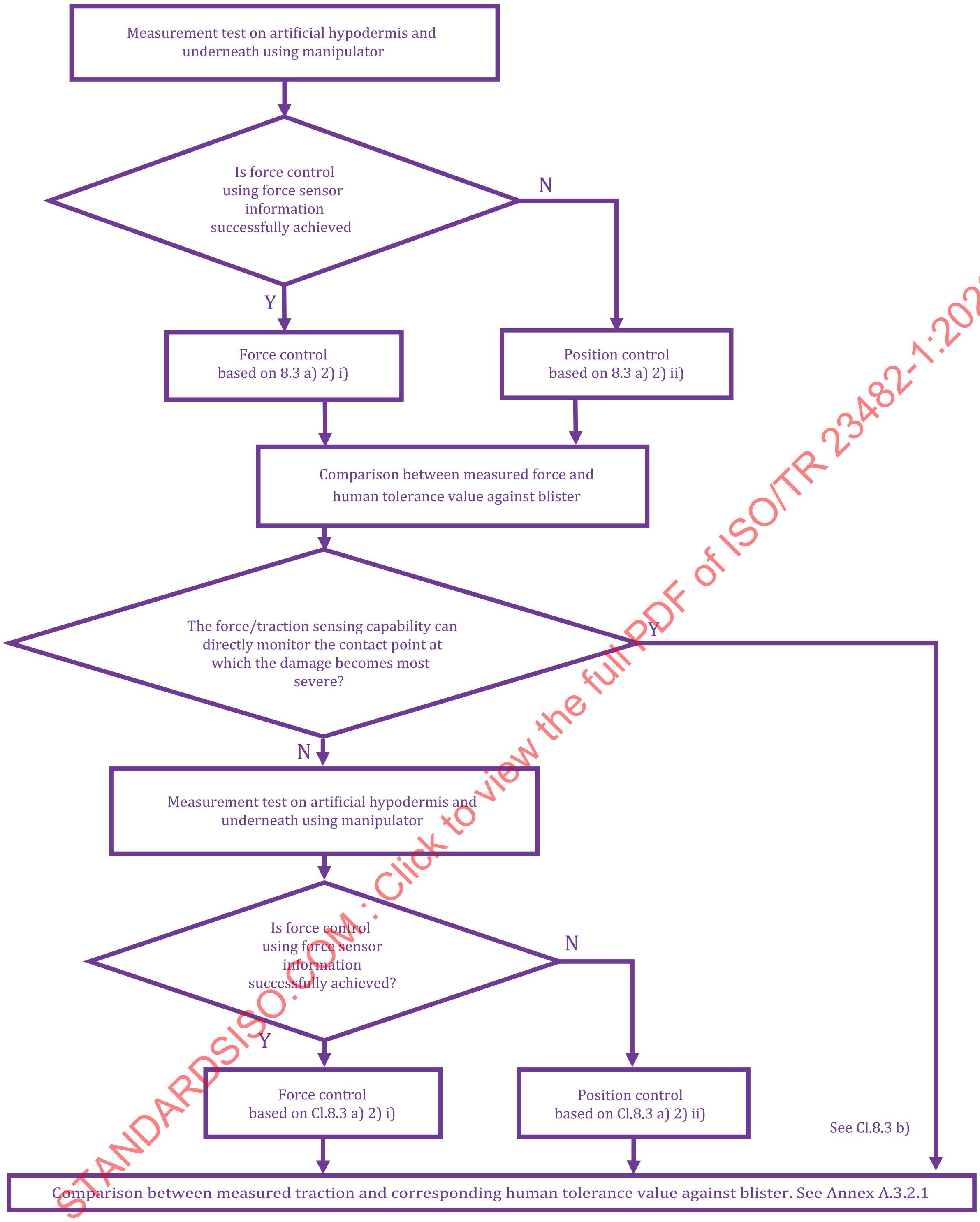


Figure 4 — Test flow

8.2 Apparatus

a) Force sensor

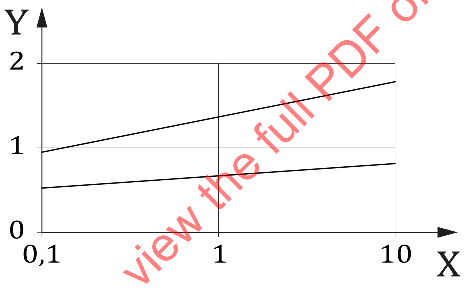
A small enough force sensor, e.g. of the size 10 × 10 mm^2 ~ 20 × 20 mm^2, is used for measuring the contact forces/tractions to observe the maximal traction.

b) Dummy for artificial skin from hypodermis and beneath

The dummy shape of the body part of interest is designed to reproduce the representative user of the robot. The dummy is made of rigid materials, such as metal, wood, and plastic. The dummy's surface is constructed in such a manner as to be shaped to simulate the surface profile of a human body part where a cuff of the physical assistant robot is attached. If the cuff is attached to a smooth human body part, such as thighs, the shape of the dummy can be simplified to fill in the gap between top and bottom shape of the human body using linear interpolation.

A piece of artificial material whose mechanical characteristics are simulated to those of human skin from hypodermis and beneath (artificial hypodermis and beneath, hereafter) is mounted on top of the dummy surface. The mechanical characteristics are evaluated to verify the following shear storage and shear loss moduli, $G'(f)$ and $G''(f)$, with their acceptable variations, as shown in Figures 5 and 6. The moduli are functions of frequency, which range from 0,1 Hz to 10 Hz. The dummy for artificial hypodermis and beneath, which has such characteristics, can be obtained by using polyurethane gel material, acrylic adhesive tape, and wound dressing. Annex B illustrates an example of constructing a multi-layered artificial hypodermis and beneath.

NOTE The shear storage and shear loss moduli in viscoelastic materials measure the stored energy representing the elastic part, and the energy dissipated as heat representing the viscous part, respectively.

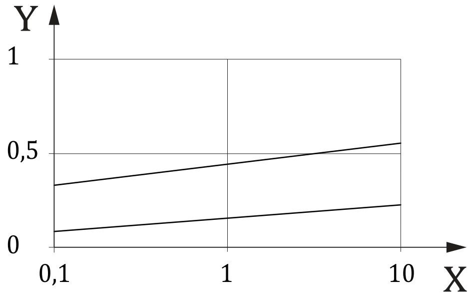


Key

X frequency (Hz)

Y G' (loss modulus) [MPa]

Figure 5 — Storage and loss modulus, $G'(f)$



Key

X frequency (Hz)

Y G'' (loss modulus) [MPa]

Figure 6 — Storage and loss modulus, $G''(f)$

In addition, by attaching a surrogate skin piece on the surface of the artificial hypodermis, this test method (see Annex E) can be used as a verification test for blister generation due to skin stress.

The dummy is fixed on a base so as not to move when force is applied from the manipulator.

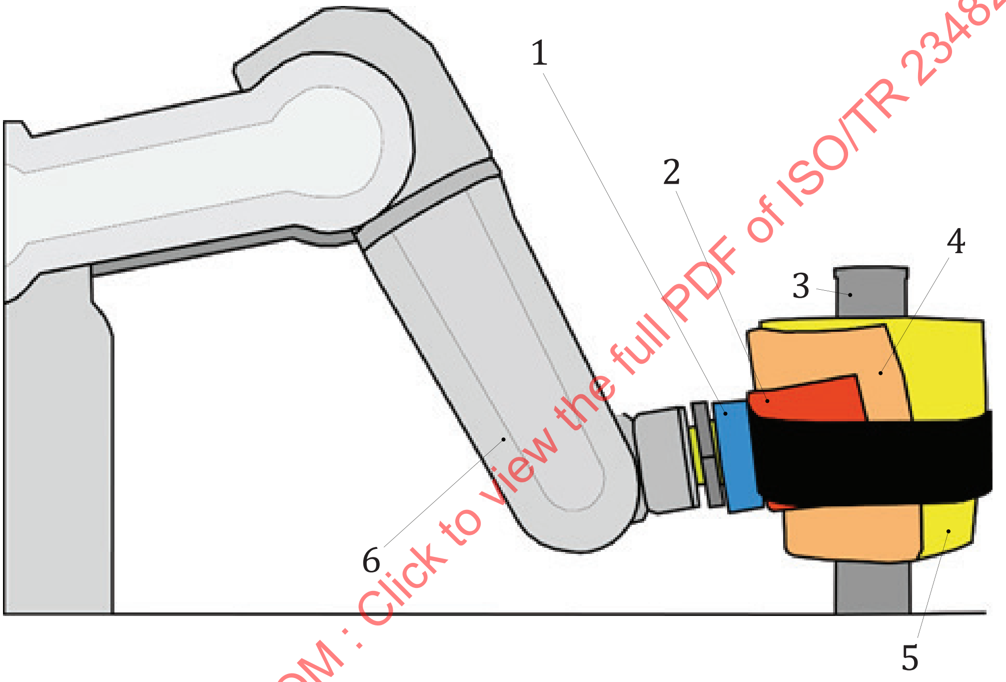
c) Cuff with force/pressure sensing capability

A cuff with force sensing capability, which is shaped to simulate the original cuff is constructed. At least, shear forces/pressures of the contact surface are measured. It is advisable to also measure normal forces/tractions, which are associated with ulcer. A cuff equipped with several force sensors distributed inside of the cuff is used.

d) Manipulator with cuff movement capability

A manipulator, which can regenerate the single/multi-axis motion of the cuff, grasps the cuff with force sensing capability described in a) (see Figure 7). It moves it repeatedly relative to the skin following the previously determined displacement data. The degrees of freedom of the manipulator can be less than six, providing the motion necessary can be regenerated.

The multi-axis force sensor is mounted between the mechanical interface of the robot and the cuff.



Key

1	force sensors [if not embedded in the cuff (see 8.3 b)]	4	surrogate skin piece inserted if necessary
2	cuff equipped with force sensors	5	dummy covered with artificial hypodermis and underneath
3	Base	6	manipulator with cuff movement capability

Figure 7 — Manipulator grasping the cuff covering upper/lower limb

e) Design of motion pattern of cuff

The motion pattern is designed a priori for the intended use (e.g. standing and sitting, walking or lifting an object). A typical interactive force pattern can be obtained as described in 8.3 a) through monitoring the force pattern by applying a cuff described in 8.2 c) to a test user.

8.3 Procedure

a) Acquisition of force pattern between human body part and cuff

The force pattern is acquired for later use as reference input data through the process described in 8.3 b) 2). The procedure of acquiring the pattern obtained at the contact surface between the human body part and the cuff is described as follows.

1) Wearing robot

A user wears a robot, whose cuff is changed to the instrumented cuff described in 8.2 c). The test will be conducted on the assumption that the user possesses the average physical size of a typical user based upon e.g. ISO 7250-1, or specified by the manufacturer. If the limitations are imposed on the physical size of the user of the target robot, modifications can be made with consultations with the manufacturer over the conditions.

2) Monitoring motion pattern on robot cuff

The robot is worn by a user, who moves with the robot in a typical use pattern. While the user moves, either forces/tractions or the relative motion of the instrumented cuff with respect to the human skin are recorded. In this case, a human monitoring device. such as a motion capture system is used to record the relative motion. Either the maximum value or the average is selected to monitor, which is specified by the manufacturer.

b) Tests

Either one of the two test cases are selected for safety validation of the robot cuff. This is shown in the test flow of Figure 4. This is not necessary, if the force/traction sensing capability can directly monitor at the contact point, at which the damage becomes severe, as shown in Figure 4. The following test sequences only deal with the measurement of shear force/traction on the artificial hypodermis and beneath, described in 8.3 b) 2). The test with surrogate skin is described in Annex E.

1) Preparations

The dummy of the body part covered with a covering of artificial hypodermis and beneath is rigidly fixed by a base. The dummy is tested as it is.

Replication of the attachment areas: The robot cuffs with the force/traction sensing capability are mounted on the mechanical interface of the manipulator and attached on the surface of the artificial hypodermis and beneath.

2) Measurement

The cuff rubs against the covering artificial hypodermis and beneath until the variance of the maximum/average value becomes small enough to show a statistically stable contact motion state.

c) Data logging

Data are processed and logged in the following procedure.

Log data of the interactive force pattern, as described either in 8.3 b) 2) or possibly in 8.3 a) 2) under the designated motion defined in 8.2 e), for later comparison with safety verification data. The example of the blister-tolerant characteristics is shown in Figure A.1.

8.4 Pass/fail criteria

The data described in A.4.3.1 can be referred to for defining pass/fail criteria for this test.

9 Test of endurance characteristics (universal)

9.1 Endurance to environmental temperature/humidity fluctuations and vibration combined with these fluctuations

9.1.1 General

This test inspects visible damage (e.g. erosion or corrosion) and functional damage (e.g. abnormalities of the control system) of a robot after exposure to environmental conditions in order to verify "durability throughout its design life" (see ISO 13482:2014, 5.11.1).

This test is applicable to all robots, but the vibration test can only be carefully applied to physical assistant robots, because they are affected by the biomechanics of their users, which are difficult to measure.

This test consists of two steps:

a) exposing the robot to a simulated environment, and

b) reporting damages and loss of functions.

Environmental conditions that can be tested include temperature, relative humidity, vibration and any combination of them. Tests can be done with single elements or combined elements. A robot that passes a combination test is treated as having passed each elemental test separately.

9.1.2 Temperature/humidity test

9.1.2.1 Test at a certain low/high temperature

The test aims at testing the robots' ability of operation and storage in low/high temperature. The two types of test methods applied are a sudden change of temperature method and a gradual change of temperature method. The details are stated in IEC 60068-2-2.

Test conditions:

- Temperature
- Time of exposure
- Temperature change rate
- Test tolerance

The parameters of test conditions are chosen from IEC 60068-2-2.

Test apparatus complies with IEC 60068-2-2.

9.1.2.2 Test during changing temperature

The test aims at testing the robot's ability of operation and storage in an environment, where the temperature is changing all the time.

There are two types of test methods:

- Temperature changes quickly within a certain period of time

  The details of test procedures, conditions and notes are stated in IEC 60068-2-14:2009 (method Na).

- Temperature changes with a pre-defined rate

  The details of test procedures, conditions and notes are stated in IEC 60068-2-14:2009 (method Nb).

9.1.2.3 Test in a high humidity environment with high temperature

The test aims at testing the robot's ability of operation, storage and transportation during relatively high humidity with constant temperature.

Test procedures, conditions, apparatus and notes are stated in IEC 60068-2-3.

9.1.2.4 Test under the environment with noticeable water

The test aims at testing the robot's ability of operation, storage and transportation during noticeable water (falling drops, impacting water and immersion)

— Test during falling water drops

This test is applicable to the robots exposed to precipitation during use. The test procedures, conditions, apparatus and notes are stated in IEC 60068-2-18:2017 (Test Ra).

— Test for water impact

The details of test procedures, conditions, apparatus and notes are stated in IEC 60068-2-18:2017 (Test Rb).

— Test for immersion

The robot is immersed wholly or partly. The details of test procedures, conditions, apparatus and notes are stated in IEC 60068-2-18:2017 (Test Rc).

9.1.3 Sealing test

Test procedures, conditions and notes are stated in IEC 60068-2-17:1994 (test Qd).

9.1.4 Robustness test

— Bump and shock

The test applies under conditions when the robot suffers from repetitive or non-repetitive shocks. The test procedures, conditions, apparatus and notes are stated in IEC 60068-2-27.

— Rough handling shocks

The test aims at assessing the robot's resistance against collision caused by improper handling and operation. The test methods can be divided into toppling and falling. The details of test procedures, conditions, apparatus and notes are stated in IEC 60068-2-31.

9.1.5 Pressure test

9.1.5.1 Test for low pressure with normal temperature

This test aims at testing the robot's ability of operation and storage in low pressure and normal temperature.

Test procedures, conditions, apparatus and notes are stated in IEC 60068-2-13.

9.1.5.2 Test for low pressure with low temperature

The test aims at testing the robot's ability of operation and storage in low pressure and gradually-changing low temperature.

Test procedures, conditions, apparatus and notes are stated in IEC 60068-2-40.

9.1.5.3 Test for low pressure with high temperature

The test aims at testing the robot's ability of operation and storage in low pressure and high temperature.

Test procedures, conditions, apparatus and notes are stated in IEC 60068-2-41.

9.1.6 Pass/fail criteria

The data described in Clause A.5 can be referred to for defining pass/fail criteria for this test.

9.2 Durability in locomotion (mobile robot)

9.2.1 Principle

This test inspects visible damage (e.g. fracture, deformation, or disengagement of parts) and functional damage (e.g. abnormalities of the control system) of a robot during continuous locomotion in order to estimate "durability throughout its design life" (see ISO 13482:2014, 5.11.1).

This test is applicable to robots that are mobile, which have the potential to cause harm to the users through mechanical or functional damage during motion.

This test consists of three steps:

a) set-up,

b) test motion, and

c) inspection.

This test uses three apparatuses:

- a test travel surface,
- a test dummy, and
- a supporting device (if necessary).

The test travel surface simulates the environment of the intended use of the robot, and typically employs a test drum or a treadmill.

The specifications of the test dummy are determined to be the maximum permissible load or according to the weight of intended users.

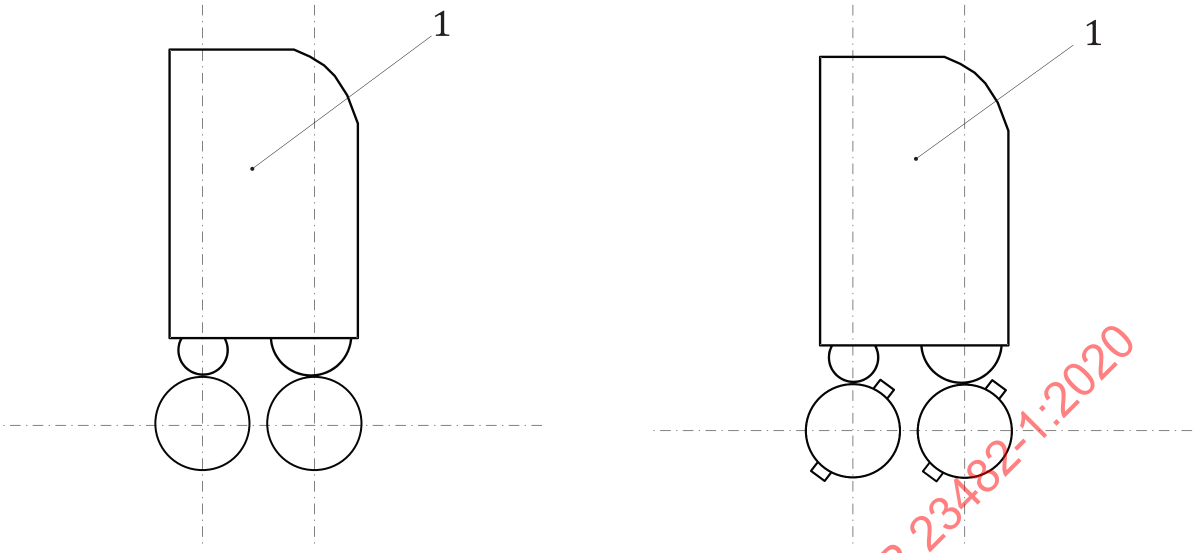
9.2.2 Apparatus

a) Test travel surface: A simulated flat travel surface of infinite length simulating the intended use environment.

   A flat travel surface of infinite length is simulated by the following options:

   - Test drum

     A test drum is applicable if the robot contacts the travel surface with a small area that is not affected by the roundness of the drum. The structure of the test drum refers to the durability test machine specified in ISO 7176-8. For a robot anticipated for outdoor use, the test is conducted on a drum with slats as defined in the above standard. For a robot anticipated for indoor use only, it is tested on a surface without slats (see Figure 8).



a) Test drum without slat (for indoor application)

b) Test drum with slat (for outdoor application)

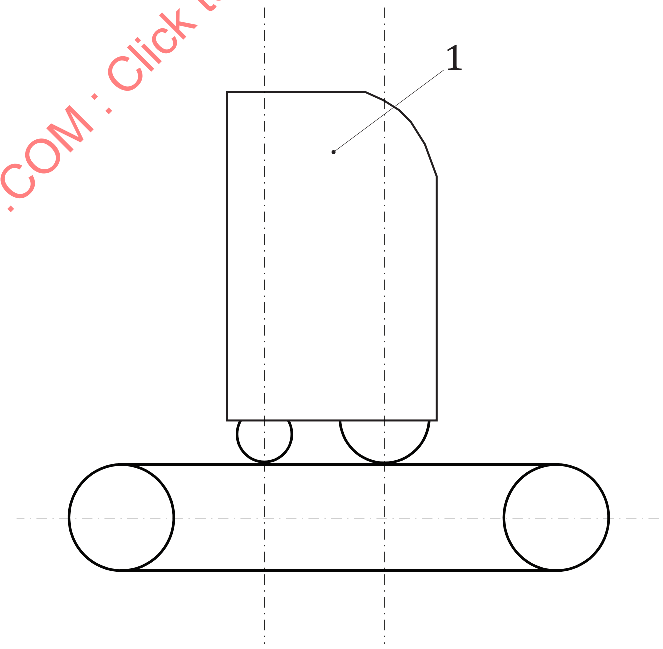
Key

1 Robot

Figure 8 — Test-drum-type test machine

— Treadmill (other types) (see Figure 9)

The treadmill is applicable to all robots except for heavy ones or the ones intended to be used on rough travel surfaces. (see Figure 9).



Key

1 Robot

Figure 9 — Treadmill-type test machine

b) Test weight

- Test dummy

  Its weight simulates that of the person onboard or the user wearing the robot, where applicable. The total weight is the maximum weight of the intended user.

  Depending on the robot's movement mechanism, the body mass distribution and kinematics of the user are simulated.

- Weight

  Its weight simulates the maximum weight specified to be loaded on the robot.

  NOTE 1 ISO 7176-11 describes a weight dummy for tests of wheel chairs.

  NOTE 2 US Code of Federal Regulations, Title 49, Part 572, Subparts E and O describe human dummies representing the 50th percentile of adult males and the 5th percentile of adult females.

  NOTE 3 ISO 10535:2006, 4.10.2.7 describes load positions for durability tests of hoists.

c) Supporting device (optional)

If the robot (such as an exoskeleton or a two-wheeled robot) is not able to maintain its posture by itself, a supporting device is applicable in order to maintain its posture. The supporting device holds the robot or a dummy, to which the robot is connected. It is important that the device does not obstruct the motion and load conditions of the robot.

9.2.3 Procedure

a) The robot is placed on the test travel surface. If the robot is able to carry passengers or to be worn by the user, the test dummy is used with the robot.

b) The robot moves on the test travel surface, at the speed specified by the manufacturer for either a time or a distance limit specified by the manufacturer. External power sources can be used as power.

c) Visible damage such as fractures, deformation, jiggling, looseness or disengagement of parts, and changes in the robot's function are recorded.

9.2.4 Pass/fail criteria

To define pass/fail criteria for this test, the data described in Clause A.6 can be referred to.

10 Test of endurance characteristics (for mobile robot)

10.1 Endurance to collision impact

10.1.1 Principle

This test inspects visible damage (e.g. fracture, deformation, or disengagement of parts) and functional damage (e.g. abnormalities of the control system) of the robot after a collision, in order to verify "durability throughout its design life" considering "maximum operational conditions derived from operation under extreme situations" (see ISO 13482:2014, 5.11.1).

This test is applicable to all robots that are mobile.

This test consists of three steps:

a) set-up,

b) collision, and

c) inspection.

The collision is performed using the same method as in 7.1.

10.1.2 Apparatus and procedure

a) The test is conducted as described in 7.1, but the robot collides directly with a barrier without a human dummy.

b) After the collision, the robot's structure is observed to record damage, deformation, wobble or looseness/fallen-off parts.

c) After the collision, the visible and functional damage is inspected and recorded.

11 Test of static stability characteristics

11.1 Principle

This test examines the stability of a robot in statically tilted conditions by confirming if the robot falls over, its load falls off or moves in a potentially dangerous manner, in order to verify that the robot design "minimizes mechanical instability" (see ISO 13482:2014, 5.10.2.1).

This test is applicable to all robots requiring mechanical static stability to avoid harm.

This test consists of two steps:

a) placing a robot on a slope, and

b) inspection.

This test uses two apparatuses:

— a slope, and

— a test dummy representing a person onboard (if necessary).

11.2 Apparatus

Slope

Test plane that is large enough to accommodate the robot and the load (if any) during test.

11.3 Procedure

a) The robot is made stable and keeps its position always perpendicular to the slope (no matter if the robot is powered on or off,) and placed on top of the slope whose angle is specified by the manufacturer. It is confirmed that the setting surface of the robot is in contact with the slope and the load on the robot is stable.

NOTE Some self-balancing robots need power on.

b) It is recorded if any part of the robot setting surface is away from the slope, the robot falls over, and/or the load falls off or moves in a potentially dangerous manner.

NOTE ISO 7176-1:2014, 3.2 describes methods to determine when the forces become zero under the uphill wheels. These include, but are not limited to, the ability to pull pieces of paper from beneath the wheels, visual identification of when the wheels lift from the test plane or the use of force-sensing instrumentation.

c) The steps a) and b) are repeated with the changes in the robot direction that represent worst-case conditions for the stability, such as forward/backward and left/right.

The weight of the carried load is the maximum specified by the manufacturer. Object(s) simulating the load are placed as specified by the manufacturer for a flat travel surface. For the person-carrier robot, the objects are loaded simulating the maximum weight and weight distribution of a person onboard. For the person carrier robot with a seated user, the dummy specified in ISO 7176-11 can be used.

11.4 Pass/fail criteria

The data described in Clause A.7 can be referred to define pass/fail criteria for this test.

12 Test of dynamic stability characteristics with respect to moving parts (for mobile robot)

12.1 Principle

This test examines the effect of moving parts and loads of the robot on the stability of the robot in order to verify that it is able to maintain stability "against static and dynamic forces from moving parts and loads of the personal care robot" (see ISO 13482:2014, 5.10.2.1).

This test is applicable to all robots with manipulators or other moving components as well as the robots that can carry loads. This test is not applicable for restraint type physical assistant robots.

The effect of moving components and loads on the stability is measured while the robot is placed on a slope. It is advisable to perform this test only after the test for static stability has been passed.

12.2 Apparatus

a) Slope

The slope is the same as described in 11.2. The sloped surface has means to secure the robot to prevent it from sliding or falling off, e.g. rope tied to a stable hook over the robot. The slope angle is equal to the maximum slope angle specified by the manufacturer.

b) Dummy loads

Objects that in size and weight simulate typical loads carried by the robot, including a dummy representing a person onboard, if necessary.

NOTE Annex C describes an apparatus that can be used to simulate shifting loads.

12.3 Procedure

a) The robot is placed on the slope in the directions that represent worst-case conditions for the stability, e.g. forward, backward, and sideways to perform b) to e) in turn. For each orientation, it is confirmed that the setting surface of the robot is in contact with the slope and the load on the robot is stable.

b) For each direction, moving parts of the robot are moved in a way that the maximum dynamic forces are generated by the moving mass in the severest condition for stability, e.g. by

- moving in the direction of the lower end of the slope;
- accelerating and stopping as fast as possible;
- applying the maximum payload to end effectors and other devices that can carry the loads.

c) If the robot is designated to carry payloads, then the payloads are applied so that the maximum dynamic forces are generated by moving the mass of the payloads in the severest condition for stability, e.g. by

   - unintentionally shifting the load in the direction of the lower end of the slope;
   - applying a load only in places in the direction of the lower end of the slope;
   - applying the maximum load.

d) If the robot is designated to carry passengers (e.g. person carrier robot) or to support the weight of a person (e.g. restraint-free type physical assistant robot), the maximum dynamic forces that can be expected from the weight of the passenger or the person being supported are applied in the severest condition for stability by simulating (e.g. using a test dummy)

   - a passenger moving abruptly in his seat or footrest;
   - a person applying or removing nearly his whole weight on the support structure of the robot.

e) For all tests, it is recorded if any part of the robot setting surface is away from the slope, the robot falls over or load falls off or moves in a potentially dangerous manner.

13 Test of dynamic stability characteristics with respect to travel (for mobile robot)

13.1 General

13.1.1 Principle

This test examines the stability of a robot or its loads in motion under typical adverse conditions in order to verify that the robot design does not cause “any hazardous rollovers, runaways, or drops of its body parts or loads being carried during travel” (see ISO 13482:2014, 5.10.3.1).

This test is applicable to robots that are mobile.

This test includes 15 travelling patterns on four types of travel surface geometries: a flat surface, an inclined surface, a stepped surface, and a gapped surface. The maximum speed tests are intended to validate the speed limit settings by the manufacturer.

13.1.2 Apparatus

a) Test travel surface

   Conditions of the test travel surface are as stated in 4.3.

b) Test dummy

   The test dummy described in Annex C can be used for the tests except the ones involving braking and turning or transient manoeuvres.

13.1.3 Procedure

If the robot uses air-filled tyres, the internal pressure is adjusted to that specified by the manufacturer.

The weight of carrying load is the maximum load specified by the manufacturer. For person carrier robots, the weight of the person onboard is simulated by a dummy weight with appropriate weight distribution. If a human needs to be physically present on the robot to operate it (i.e. programming motion or remote control is not possible), all necessary precautions are taken to ensure the safety of the test person onboard during the tests as described in 4.4. If an object is loaded on the robot's load area, it is loaded in the method specified by the manufacturer.

13.2 Stability test on a flat surface

13.2.1 Braking test on split surface

a) The friction coefficient of the right half of the test travel surface is maintained at no less than 0,75. The friction coefficient of the left half of the test travel surface is maintained no greater than 0,30. The friction coefficients are measured in accordance with 4.3.

b) The robot travels along the centreline of the travel surface from the start position, as shown in Figure 10 a) and accelerates to the maximum speed in the acceleration section.

c) After passing the braking start position while maintaining the maximum speed, the robot brakes with the maximum braking force and comes to a halt. If the robot has more than one braking methods, tests are conducted for each method.

d) Whether the specified test speed is achieved at the braking start position is checked.

e) Whether or not the robot falls over, or the person onboard or the load falls from start to stop is logged.

NOTE The friction coefficient no greater than 0,30 can be represented using baby powder, etc., mixed with water. After the test, tyres can be cleaned easily. If needed, contaminated tyres can be replaced.

13.2.2 Acceleration test on split surface

a) The robot travels along the centreline of the travel surface from the start position, as shown in Figure 10 b), and accelerates to 80 % ± 10 % of the maximum speed in the acceleration section.

b) After passing the full acceleration start position, the robot is accelerated at its maximum rate.

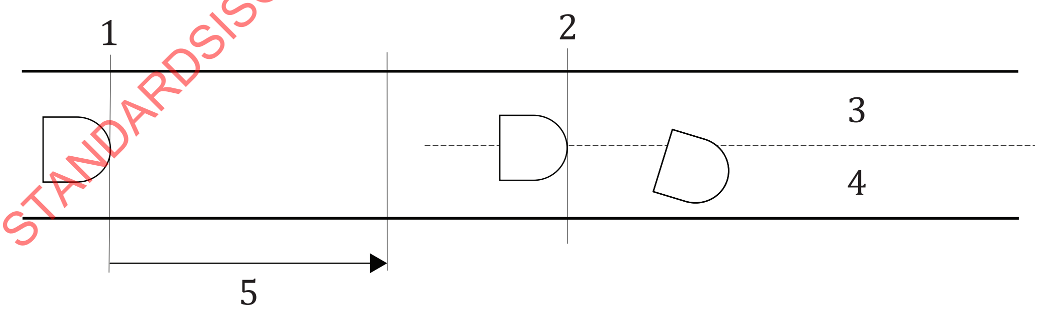
c) Whether specified speed is achieved in the acceleration section is checked. Whether or not the robot falls over, or the person onboard or the load falls from start to stop is logged.

13.2.3 Acceleration test from stationary condition

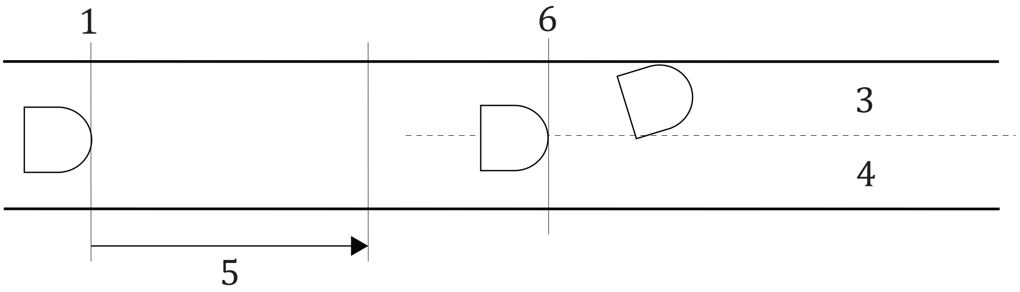
a) The robot is placed on the full acceleration start position along the centreline of the travel surface, as shown in Figure 10 c).

b) The robot is accelerated at its maximum rate from stationary condition.

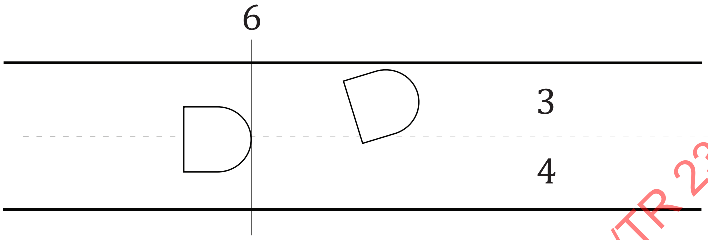
c) Whether or not the robot falls over, or the person onboard or the load falls is logged.



a) Braking from maximum speed



b) Acceleration during travel



c) Acceleration from stationary condition

Key

1	start position
2	braking start position
3	low friction surface
4	high friction surface
5	acceleration section
6	full acceleration start position

Figure 10 — Braking and acceleration test on split surface

13.3 Stability test on inclined surface

13.3.1 General

This test is conducted if inclined surfaces are anticipated in the robot use environment.

The inclined angle of the test travel surface is the maximum angle specified by the manufacturer on which the robot is operable.

13.3.2 Maximum speed test on downward slope

a) The robot travels along the centreline of the inclined travel surface, as shown in Figure 11, and accelerates to the maximum extent in the acceleration section.

b) The robot passes through the measurement section while maintaining the maximum speed and then stops. The length of the measurement section is set so that the time over the measured distance is no less than 1 s.

c) The time over the measurement section is measured.

d) Measurements are repeated at least four times to determine the average time over the measurement section (T).

e) The maximum speed (V) is calculated by the following formula:

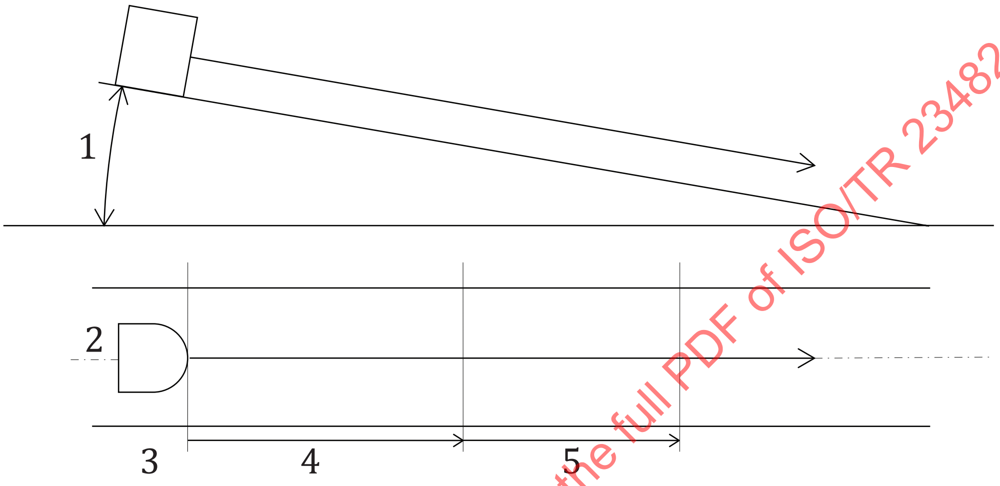
$$V = \frac{L}{T}$$

where

V is the maximum speed (m/s);

L is the length of the measurement section (m);

T is the average time over the measurement section (s).



Key

1 inclined angle
2 robot
3 start position
4 acceleration section
5 speed measurement section

Figure 11 — Test method for downward slope maximum speed test

13.3.3 Downward slope acceleration and braking test

a) The robot is placed at the start position on the inclined surface, as shown in Figure 12.

b) The robot starts toward the downward slope at the maximum acceleration.

c) The robot travels along the centreline of the test travel surface, accelerating to the maximum speed in the acceleration section.

d) It brakes with the maximum braking force after passing by the brake start position and stops. If the robot has more than one braking method, tests are conducted for each method.

EXAMPLE Braking in normal operation; braking for a protective stop; braking for an emergency stop.

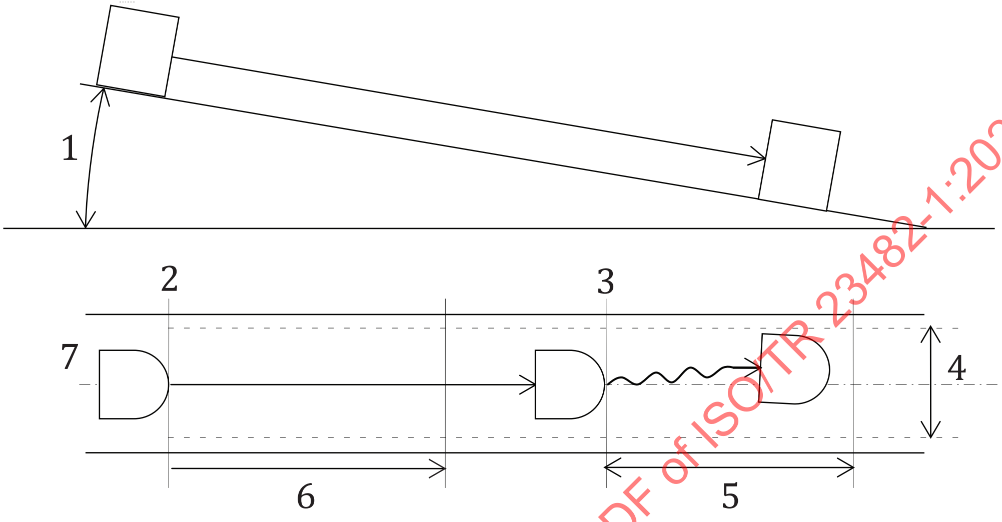
e) Whether or not a part of the robot deviated from the stop distance specified in the robot specifications is logged.

f) Whether or not a part of the robot deviated from the allowed width in its specifications from the brake start position to the brake stop position is logged.

g) Whether or not the robot falls over or the person onboard or the load on the robot falls from start of braking to stop is logged.

h) Whether specified test speed is achieved at the braking start position is checked.

NOTE The purpose of the test is not to measure the braking distance, but to confirm that a robot never deviated the allowed distance nor the allowed width and confirm the stability of a robot in braking.



Key

1	inclined angle
2	start position
3	brake start position
4	allowed width
5	allowed braking distance
6	acceleration section
7	robot

Figure 12 — Test method for downward slope acceleration and braking test

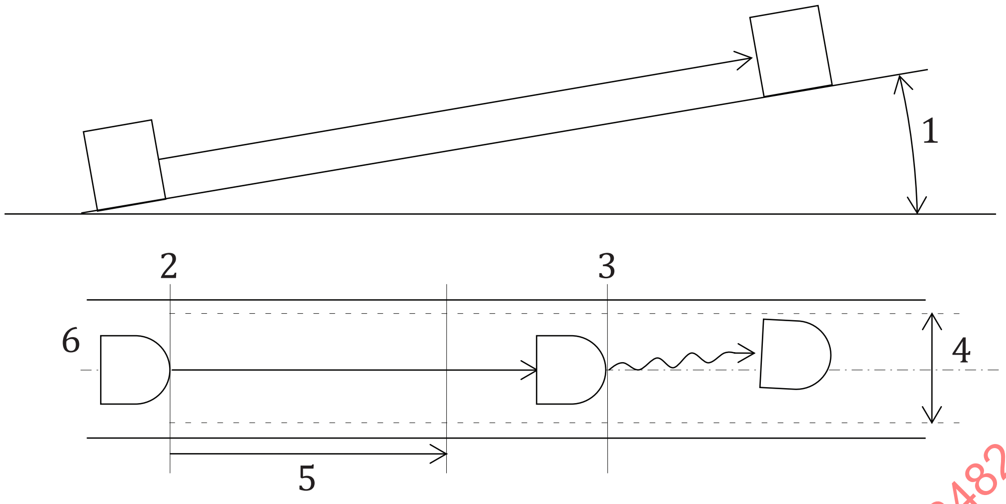
13.3.4 Upward slope acceleration test

a) The robot is placed on the start position on the inclined surface, as shown in Figure 13.

b) The robot starts toward the upward slope at the maximum acceleration.

c) The robot travels along the centreline of the test travel surface, accelerating to the maximum speed in the acceleration section.

d) Whether or not the robot falls over or the person onboard or the load on the robot falls is logged.



Key

1 inclined angle
2 start position
3 brake start position
4 allowed width
5 acceleration section
6 robot

Figure 13 — Test method for upward slope acceleration and braking test

13.3.5 Downward slope full turn test

This test is applicable to robots capable of turning the direction while cruising.

a) The robot accelerates to the maximum speed designated for turning manoeuvre in the acceleration section, as shown in Figure 14.

b) While maintaining the maximum speed, it makes a full turn with the minimum radius immediately after passing the turn start position until turning roughly around 180°.

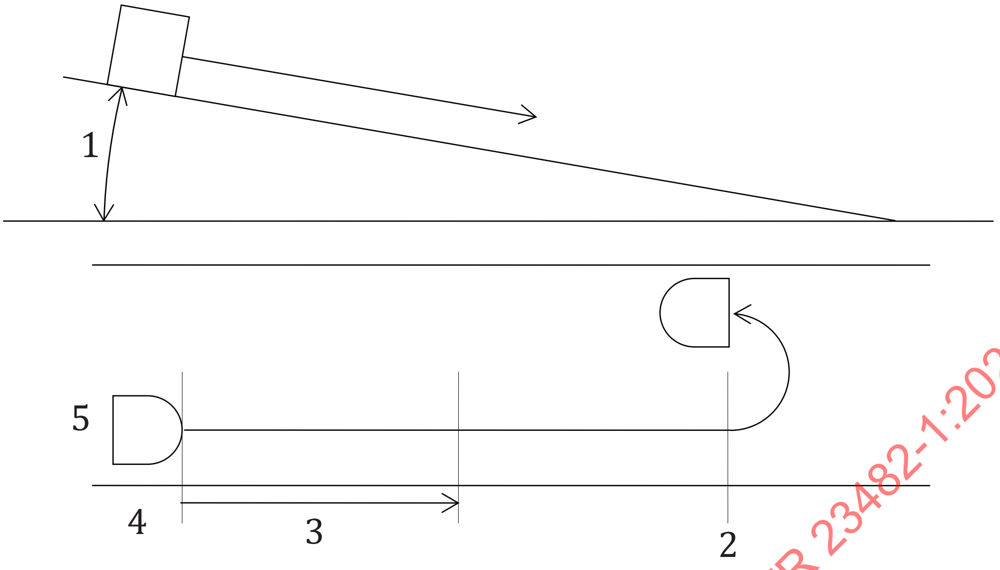
c) If the robot is capable of making a pivot turn, it stops travelling and makes a pivot turn until rotating no less than 360°.

d) Whether specified test speed is achieved at the turn start position is checked.

e) Whether or not the robot falls over or the person onboard or the load on the robot falls is logged.

f) The test is conducted in both the clockwise and the counter-clockwise directions.

NOTE By modifying the maximum steering angle of the robot, the speed in this test can be lowered while preserving the maximum lateral acceleration if the acceleration section does not have enough length for the robot to attain the maximum speed.



Key

1 inclined angle
2 turning position
3 acceleration section
4 start position
5 robot

Figure 14 — Test method for the downward slope full turn test

13.3.6 Inclined surface crossing test

a) The robot travels along the centreline of a test travel surface on a laterally inclined surface, as shown in Figure 15, and accelerates to the maximum speed in the acceleration section.

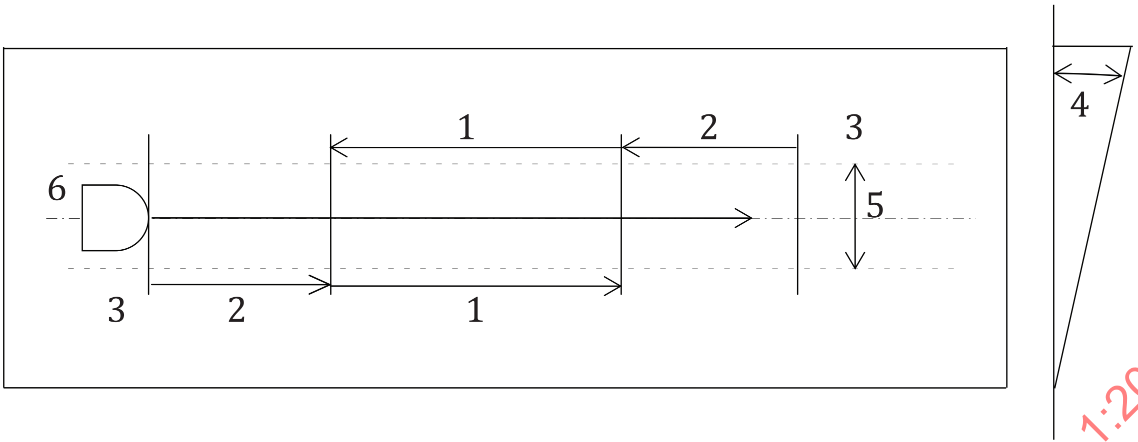
b) While maintaining the maximum speed, the robot passes through the observation section and stops.

c) In the observation section, whether a part of the robot has deviated from the allowed width of the travel surface specified in its specifications is logged.

d) Whether the specified test speed is achieved in the observation section is checked.

e) Whether or not the robot falls over, or the person onboard or the load falls from start to stop is logged.

f) The steps a) to e) are repeated in the opposite travelling direction on the same test travel surface.



Key

1 observation section
2 acceleration section
3 start position
4 inclined angle
5 allowed width
6 robot

Figure 15 — Test method for inclined surface crossing test

13.3.7 Pivot turn on inclined surface test

This test applies to robots that maintain their balance through stability control systems.

a) The robot is placed on an inclined surface and balanced in a stationary condition.

b) The robot makes a pivot turn until it loses a balance or completes ten turns, whichever smaller.

c) The step b) is repeated in the opposite turning direction.

d) Whether or not the robot falls over, or the person onboard or the load falls is logged.

13.4 Stability test for steps and gaps

13.4.1 General

This test is conducted if steps and gaps are anticipated in the use environment of a robot.

The height of the step is the operable maximum height in the robot specifications for both upward and downward movements. If not specified in the specifications, the height can be set at 50 mm for robots that operate outdoors or 20 mm for robots that operate indoors.

The width and depth of the gap are the operable maximum values specified in the robot specifications. The upper edges of the step and the gap are rounded with the radius of 3 mm (+2, −0) as defined in ISO 7176-10.

13.4.2 Moving upward from stop position

a) The robot is placed so that its front wheel is in contact with the step, as shown in Figure 16 a). Here, the angle of the step to the robot travel direction is the angle at which the robot is operable according to its specifications but with the greatest impact on the stability. If the angle to the step is not specified in the specifications, it can be set at 90° ± 5°. The wheels of the robot are positioned in the forward direction.

b) The robot starts at the maximum power output to go up the step and stop.

c) Whether or not the robot falls over, or the person onboard or the load falls, or the robot is damaged when passing over the step is logged.

13.4.3 Moving up at maximum speed

a) The robot travels from the start position and accelerates to the maximum speed in the acceleration section, as shown in Figure 16 b).

b) The robot moves up the step and stops. In doing this, the entry angle to the step is that in which the robot is operable according to its specifications but with the greatest impact on the stability. If the entry angle is not specified in its specifications, the angle can be set at 90° ± 5° and 10° ± 5°.

c) Whether the specified test speed is achieved is checked.

d) Whether or not the robot falls over, or the person onboard or the load falls, or the robot is damaged when passing over the step is logged.

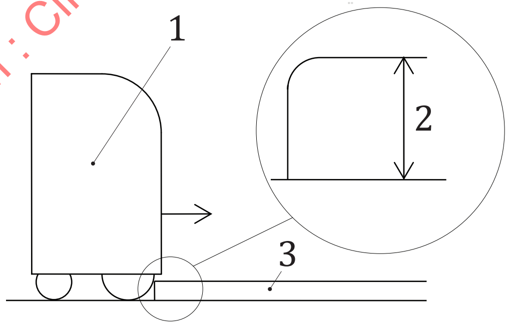
13.4.4 Moving up while accelerating

The following procedures apply to robots that maintain their balance by the wheel torque and can become unstable when losing contact between the wheels and the floor after moving up the step.

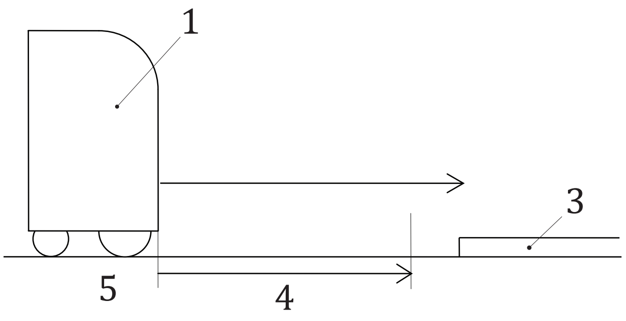
a) The robot travels from the start position and accelerates to 80 % ± 10 % of the maximum speed in the acceleration section, as shown in Figure 16 c).

b) The robot moves up the step and the wheels are accelerated just passing the step.

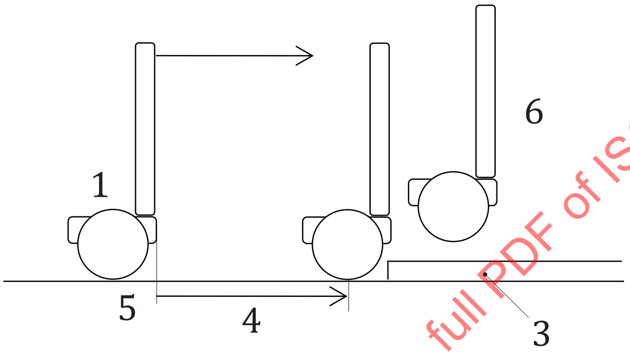
c) Whether or not the robot falls over, the person onboard or the load falls, or the robot is damaged when passing over the step is logged.



a) Moving up from stop position



b) Moving up at maximum speed



c) Wheel acceleration without contact between wheels and floor

Key

1	robot
2	height of step
3	step
4	acceleration section
5	start position
6	wheel acceleration

Figure 16 — Test method for up step test

13.4.5 Descending step at low speed

a) The robot is placed so that its front wheel is at the end of the step, as shown in Figure 17 a). Here, the angle of the step to the robot travel direction is the angle at which the robot is operable according to its specifications but with the greatest impact on the stability. If the angle to the step is not specified in the specifications, it can be set at 90° ± 5°. The wheels of the robot are positioned in the forward direction.

b) The robot travels at very slow speed and goes down the step and stops.

c) Whether or not the robot falls over, the person onboard or the load falls, or the robot is damaged when passing over the step is logged.

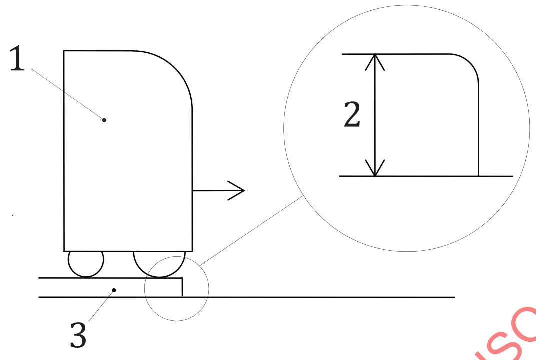
13.4.6 Descending step at maximum speed

a) The robot travels from the start position and accelerates to the maximum speed in the acceleration section, as shown in Figure 17 b).

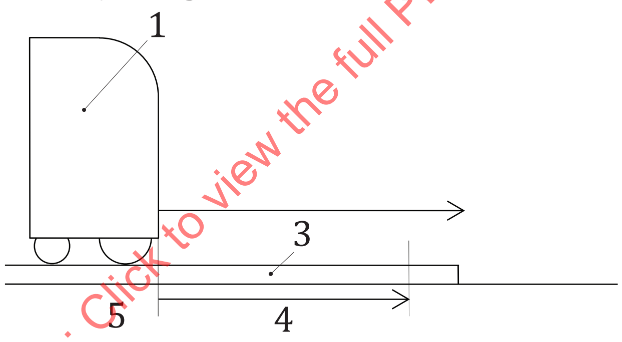
b) The robot moves down the step maintaining the maximum speed and stops. The angle of the step in the robot travel direction is the angle at which the robot is operable according to its specifications but with the greatest impact on the stability. If the angle of the step is not specified in the specifications, it can be set at 90° ± 5°and 10° ± 5°.

c) Whether the specified test speed is achieved is checked.

d) Whether or not the robot falls over, the person onboard or the load falls, or the robot is damaged when passing through the step is logged.



a) Going down from stop position



b) Going down at maximum speed

Key

1 robot
2 height of step
3 step
4 acceleration section
5 start position

Figure 17 — Test method for down step test

13.4.7 Gap crossing test

a) The robot is placed close to the gap, as shown in Figure 18 a). The angle of the gap in the robot travel direction is the angle at which the robot is operable according to its specifications but with the greatest impact on the stability. If the angle to the gap is not specified in the specifications, it can be set at 90° ± 5°. The wheels of the robot are positioned in the forward direction.

b) The robot travels at a very slow speed and crosses the gap and stops.

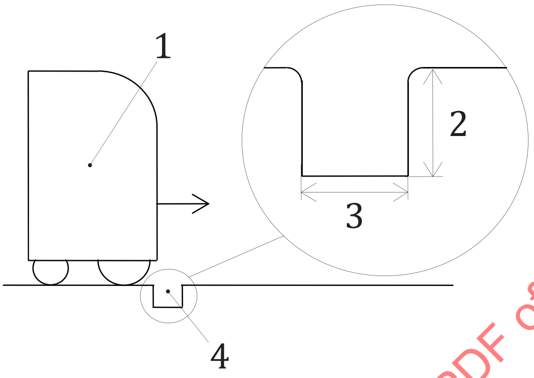
c) Whether or not the robot falls over, the person onboard or the load falls, or the robot is damaged when passing over the step is logged.

d) The robot travels from the start position and accelerates to the maximum speed in the acceleration section, as shown in Figure 18 b).

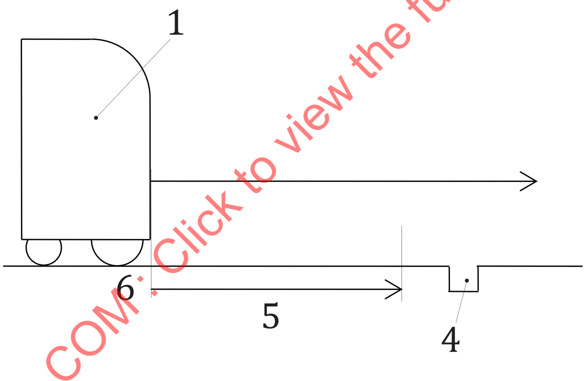
e) The robot crosses the gap maintaining the maximum speed and stops. The angle of the step to the robot travel direction is the angle at which the robot is operable according to its specifications, but with the greatest impact on the stability. If the angle to the step is not specified in the specifications, it can be set at 90° ± 5°and 10° ± 5°.

f) Whether the specified test speed is achieved is checked.

g) Whether or not the robot falls over, or the person onboard or the load falls when passing across the gap is logged.



a) Crossing from stop position



b) Crossing at maximum speed

Key

1	robot
2	depth of gap
3	width of gap
4	gap
5	acceleration section
6	start position

Figure 18 — Test method for gap crossing test

13.5 Pass/fail criteria

The data described in Clause A.8 can be referred to for defining pass/fail criteria for this test.

14 Test of safety-related control functions (universal)

14.1 Test of integration of electro-sensitive protective equipment (ESPE)

14.1.1 Principle

This test is not necessary if the robot is intended to be used only in environments covered by the applicable parts of IEC 61496

Where the ESPE applied is used outside of the scope of the applicable part of IEC 61496, the ESPE complies with the requirements of EN 62998-721 and the following test.

This test includes three optional test conditions:

a) outdoor lighting interference (for maintaining failure-to-safety),

b) low lighting level (for maintaining failure-to-safety), and

c) indoor lighting interference (for maintaining failure-to-safety).

Test instruments are the following apparatuses:

— test pieces (black, white, grey, and retro-reflective),

— backgrounds (black, white, and grey),

— light sources (incandescent light, fluorescent light, stroboscopic light, and artificial sunlight).

Unless appropriate to the robot feature, the test conditions are chosen to fit it.

NOTE ISO 13482 can require other tests with reference to IEC 61496, a series of safety standards applicable for safety-related non-contact sensing devices (ESPE).

14.1.2 Sampling

The samples are the ESPE mounted on the robot.

14.1.3 Apparatus

a) Test piece

The test piece is either spherical or cylindrical in size that is reasonably foreseeable for an object expected to be detected by the ESPE, or otherwise it is a cylindrical test piece as defined in ISO 13856-3.

EXAMPLE 1 In order to simulate a human torso, the test piece can be a cylinder with 0,6 m height and 0,2 m diameter.

EXAMPLE 2 In order to simulate a human arm or leg, the test piece can be a cylinder with 0,4 m height and 0,07 m diameter.

The optical surface conditions of the test piece simulate the conditions that are most difficult to be detected among the objects anticipated to be hardly detected by the ESPE, or otherwise they can comply with the following four types of the surface conditions specified in IEC/TS 61496-4-3:

1) Black surface (with a diffuse reflectance value of less than 5 %, within the scope of wavelength covered by the sensor),

2) Grey surface (with a diffuse reflectance value of 27-33 %),

3) White surface (with a diffuse reflectance value of more than 70 %), and

   4) Retro-reflective surface.

b) Background

   The background colour simulates the worst case for detection among the environments where the ESPE are used, or otherwise use any of the following 3 colours specified in IEC/TS 61496-4-3:

   1) Black;
   2) Grey;
   3) White.

c) Light source

   1) Artificial sunlight;
   2) Indoor lighting.

   The indoor lighting is the light source used where the ESPE is used. If it is not specified, any of the following types of light source specified in IEC 61496-3, IEC/TS 61496-4-2 or IEC/TS 61496-4-3 is used:

   - Incandescent light;
   - Fluorescent light;
   - Stroboscopic light.

14.1.4 Procedure

14.1.4.1 General

The ESPE is tested by being mounted on a robot that is operated in a static condition or otherwise under an equivalent condition.

Tests are conducted for all presumable combinations of the test pieces and backgrounds. The movement speed of the test piece is the maximum that is reasonably foreseeable, or otherwise 1,6 m/s (see ISO 13855).

14.1.4.2 Outdoor environment test

a) The artificial sunlight is turned on and is directed along the optical axis of the sensor.

b) The ESPE is turned on.

c) Without any object in the detection zone, behaviour of the ESPE is observed for a period of at least 5 s unless otherwise specified by the manufacturer for a period.

d) The test piece is brought into the detection zone and the response of the ESPE is observed for a period of at least 5 s unless otherwise specified by the manufacturer for a period.

e) The test piece is removed from the detection zone and response of the ESPE is observed for a period of at least 5 s unless otherwise specified by the manufacturer for a period.

f) The power of the device is turned off for 5 s.

g) The steps b) to f) are repeated at least four times.

h) The artificial sunlight is shaded periodically by a black panel so that the light intensity alternately changes with a period of no greater than 2 s each.

i) The steps b) to f) are repeated at least four times.

14.1.4.3 Low lighting test

a) The indoor lighting condition with the lowest light intensity specified by the manufacturer is used as the test condition. If it is not specified, the tests are conducted with both the incandescent and the fluorescent light with intensity less than 50 lx.

b) The ESPE is turned on.

c) Without any object in the detection zone, behaviour of the ESPE is observed for a period of at least 5 s unless otherwise specified by the manufacturer for a period.

d) The test piece is brought into the detection zone and response of the ESPE is observed for a period of at least 5 s unless otherwise specified by the manufacturer for a period.

e) The test piece is removed from the detection zone and response of the ESPE is observed for a period of at least 5 s unless otherwise specified by the manufacturer for a period.

f) The power of the ESPE is turned off for 5 s.

g) The steps b) to f) are repeated at least four times.

h) The ESPE is turned on.

i) The intensity of the ambient lighting is lowered to 50^{th} percentile of the anticipated lighting intensity, and is gradually lowered to the lowest limit. The limit and the decreasing speed are specified by the manufacturer. Whether the ESPE shows any hazardous failure is observed.

14.1.4.4 Indoor lighting interference test

a) The indoor lighting condition with the lowest light intensity specified by the manufacturer is used as the test condition. If it is not specified, the tests are conducted with both the incandescent and the fluorescent light with the light intensity between 100 lx to 300 lx. As an indoor interference light, light sources specified by the manufacturer are used. If it is not specified, the tests are conducted with the three types of the light sources in 14.1.3 c)2).

b) The indoor interference light source is turned on and its direction is set to cause the highest light intensity to the sensor.

c) The ESPE is turned on in normal operation

d) Without any object in the detection zone, behaviour of the ESPE is observed for a period of at least 5 s unless otherwise specified by the manufacturer for a period.

e) The test piece is brought into the detection zone and behaviour of the ESPE is observed for a period of at least 5 s unless otherwise specified by the manufacturer for a period.

f) The test piece is removed from the detection zone and behaviour of the ESPE is observed for a period of at least 5 s unless otherwise specified by the manufacturer for a period.

g) The power of the ESPE is turned off for 5 s.

h) The steps c) to g) are repeated at least four times.

14.2 Test of operation in slippery environments

14.2.1 Principle

This test examines the ability of the robot to operate safely in slippery environments (see ISO 13482:2014, 5.15).

If it is assumed in risk assessment that the robot is able to detect slippery ground conditions, the detection capability and the proper reaction on slippery surfaces are evaluated.

14.2.2 Apparatus and procedure

a) The first step tests if the robot can operate properly at the minimum friction coefficient set specified by the manufacturer. Therefore, all the standard safety tests for braking, turning, holding course at the maximum allowable slope, are performed on a surface with the set friction (e.g. using specific slippery materials). The friction coefficient is measured with the robot itself in several directions.

NOTE The friction value can be measured by blocking the tyres of robot and pulling the whole robot.

b) The second step verifies that the robot automatically detects when the friction coefficient is below the critical value specified by the manufacturer. The tests are performed with a different slippery surface with a coefficient 10 % below the critical value and consist of the same manoeuvres as before.

14.3 Electromagnetic immunity

14.3.1 Principle

This test examines safety-related functions of a robot in order to verify the designs to protect it from “all reasonably foreseeable electromagnetic disturbances” (see ISO 13482:2014, 5.8.1).

This test is applicable to robots that have safety functions in their control system.

14.3.2 Apparatus

a) Common equipment and environments

The equipment and environments for testing electromagnetic disturbance conform to applicable standards for the intended use and environment (e.g. IEC 61000-4-2, IEC 61000-4-3, IEC 61000-4-4, IEC 61000-4-5, IEC 61000-4-6, IEC 61000-4-8, IEC 61000-4-11 and ISO 7176-21).

b) Instruments for each type of robot

- Instruments for supporting a mobile robot in an operable condition without moving its position e.g. rollers to support the tyres of robot.
- Instruments that enable remote operation of safety-related functions (e.g. pushing a robot stop button). They are indispensable in commanding a robot manually in an anechoic chamber (see IEC 61000-4-3).
- Instruments capable of monitoring and recording robot movements (e.g. stopping or rotation of tyres) in an anechoic chamber are applicable. The instruments have a function to record data in time series if the reaction time of the safety-related function under the test is critical to its capability.

When these instruments are installed around the robot, they cannot be made of metal or other materials that have a significant influence on the electromagnetic field. These instruments are not affected by the applied electromagnetic disturbance.

14.3.3 Procedure

a) Specifications of the electromagnetic disturbance to be applied are selected from IEC 61000-6-1, IEC 61000-6-2, IEC 60204-1, IEC 61326-3-1, etc., so that they match the environment where the robot is used.

b) The robot is placed in the anechoic chamber as specified by the standards. The support instruments to fix the robot position are applied if necessary.

c) The robot is prepared to activate its safety-related function. Activation of the function can be commanded remotely by additional instruments.

d) The electromagnetic disturbance is applied to the robot. The disturbance lasts for a sufficient period determined by the nature of the safety-related function under the test.

e) The robot is commanded to activate the safety-related function under the test.

f) The response of the robot is recorded.

g) The robot is restarted if its control is lost.

h) Steps c) to g) are repeated for all specifications of the electromagnetic disturbance selected in a) for all the safety-related functions to be tested.

i) The recorded data are compared with those in the expected behaviour of the safety-related functions.

NOTE It is advisable to automate the test since an extremely large number of the electromagnetic disturbances to be examined are specified in the standards.

15 Response to safety-related obstacles on the ground (for mobile robot)

15.1 Distance of protective stop

15.1.1 Principle

This test measures the distance between a robot and a simulated safety-related obstacle (e.g. a moving human) at the moment the robot finishes a protective stop in order to verify the designs for “sufficiently reduced risk of hazardous collisions with safety-related obstacle” (see ISO 13482:2014, 5.10.8.1).

This test is applicable to all robots that are mobile and have collision avoidance functionality realized by non-contact sensors to operate a protective stop.

This test consists of three steps:

a) setting up,

b) performing test motions, and

c) detecting the moment of stopping and measuring the distance.

This test uses a motion tracking device, a travel surface, and test pieces.

The test motions are configured as combinations of three factors:

- the travel direction of the robot (forward, backward, right, and left, if capable),
- the travel direction of the obstacle (forward, backward, right, and left, if movable), and
- the lateral relative position between the robot and the obstacle (centre, right end, left end), under representative speeds.

Test pieces are the following obstacles: a standing human, a wall, and a perpendicular post of 25 mm in diameter. Unless appropriate to the robot feature, the test conditions are chosen to fit it.

15.1.2 Apparatus

a) Test piece

Objects with surface conditions and dimensions to represent safety-related obstacles that the robot is likely to encounter under the conditions of use specified by the manufacture. If safety-related obstacles are anticipated to move, the test piece is equipped with equivalent movement capability.

If the anticipated safety-related obstacles are not specified by the manufacture, the following three objects are used instead.

1) Wall

   - Wooden board, 90 cm in length and 90 cm in width
   - Cloth, 90 cm in length and 90 cm in width, with reflectance ratio of under 10 %
   - Mirrored board, 90 cm in length and 90 cm in width, with reflectance ratio of more than 90 %
   - Transparent board, 90 cm in length and 90 cm in width, with translucency ratio of more than 80 %
   - Fence-shaped wall, with a frame 90 cm in length and 90 cm in width, with the stakes being either round rods or pipes with a diameter of 10 mm set at intervals of 100 mm. The grid is oriented vertically and made of steel or another metal such as aluminium, selected to simulate the intended use environment

The colour or pattern of the wall and colour of the floor correspond to the intended use environment.

2) Cylindrical post

   Round rods or pipes, 25 mm in diameter and more than 90 cm in length, made of metal, resin or wood, selected to simulate the intended use environment.

3) Test dummy

   Full body-type mannequins with the size ranging from infants to adults, are selected to simulate the intended use.

   Clothing of the mannequin, if black is specified, has the least minimum reflectance value of the official diffuse reflectance rate of 1,8 %.

   The material of the mannequin does not damage the robot or the surrounding facilities, etc., even in collision.

   For lower-body mannequins, a mechanism that can simulate walking movement is advisable.

   NOTE The mannequin can be replaced with cylindrical test pieces as defined in ISO 13856-3.

b) Test travel surface

A travel surface which represents the anticipated robot use environment is used. If the braking distance differs depending on the surface, the surface that causes the longest braking distance is used.

It also has adequate length and width for the robot to slow down and stop after acceleration to a normal travel speed.

c) Motion tracking device (for tests with moving obstacles)

A device that is capable of filming the target markers (reflective material spheres or blinking marks, etc.) fixed on the robot and/or the moving test piece, at frame rates corresponding to the robot's travel speed. The motion tracking device is able to determine positions of the robot and the test piece with a precision of ±5 mm and the orientations of the robot and test piece with a precision of ±2°.

15.1.3 Procedure

a) The robot and the test piece are placed on a test travel surface with a distance longer than the maximum sensing range of the robot. All combinations of the conditions below are tested.

  1) Travel direction of robot

    i) Normal travel direction.

    ii) 90° from the normal travel direction, if applicable.

    iii) 180° from the normal travel direction, if applicable.

    iv) 270° from the normal travel direction, if applicable.

  2) Facing angle of test piece [see Figure 19 a)]

    i) 90° ± 5° to the travel path of the robot.

    ii) 45° ± 5° to the travel path of the robot.

  3) Position of test piece

    i) The centre of the test piece is positioned on the centre line of the robot travel path.

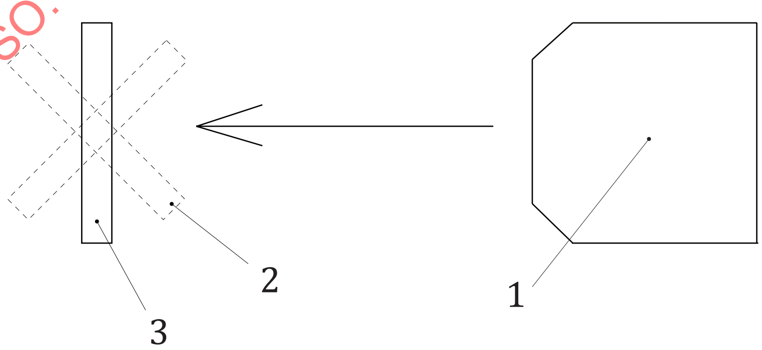
    ii) The left side of the test piece is aligned with the right side of the robot in the travel direction [see Figure 19 b)].

    iii) The right side of the test piece is aligned with the left side of the robot in the travel direction [see Figure 19 c)].

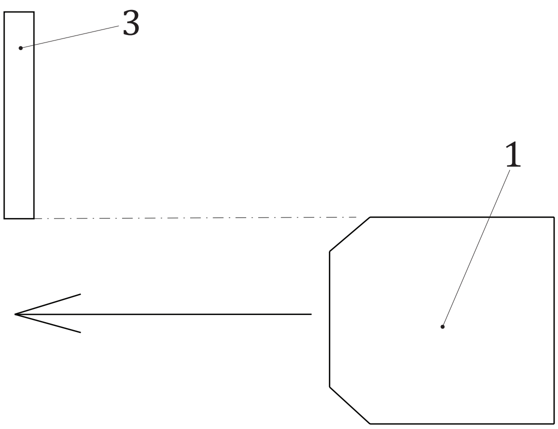
    iv) If the test piece is intended to simulate a moving object, the test piece is moved straight at the speed so as to cross over the robot travel path to encounter the robot in the directions of 90°, 180° and 270°.

b) The robot travels at its typical speed under intended use conditions.

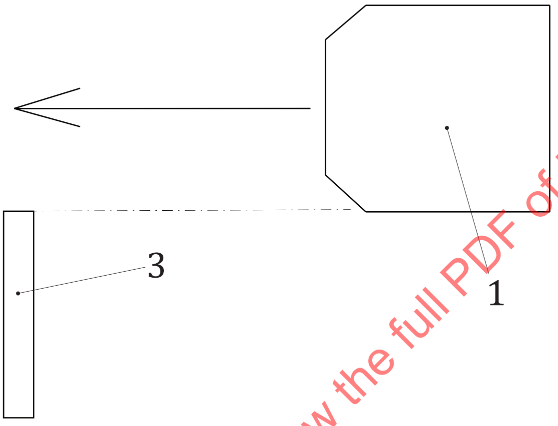
c) The shortest distance between the robot and the test piece at the moment the robot has completely stopped is measured. In case of moving a test piece, the movement of both the robot and the test piece are tracked by the motion tracking device to identify the distance at the moment when the robot speed has become zero.



a) Centre of the test piece and the centre of the robot



b) Left end of the test piece and right end of the robot



c) Right end of the test piece and left end of the robot

Key

1	robot
2	45° obstacle
3	90° obstacle

Figure 19 — Lateral relative position between the robot and the obstacle

15.2 Distance and speed in safety-related speed control

15.2.1 Principle

This test measures the speed of a robot and the distance between a robot and a simulated safety-related obstacle simultaneously in order to evaluate “safety-related speed control” (see ISO 13482:2014, 5.10.8.3). The goals of this test are both to verify that the robot is able to maintain the safety-related speed and the safety distance from the obstacle, and to validate the safety-related speed control based upon the verified data.

This test is applicable to all robots that are mobile and have safety-related speed control functionality.

This test is implemented using the same method as the test in 15.1.

NOTE ISO 13482:2014, Annex C, specifies the safety criteria between the speed and the distance of the safety-related speed control.

15.2.2 Apparatus and procedure

This test is performed in the same way as the test of distance of protective stop (see 15.1). The motion tracking device is used to measure both the position and the speed during entry of an obstacle in the safeguarded space. The robot reaction to the obstacle and the relative approach speed of both obtained from the motion tracking device are monitored and recorded.

15.3 Distance of stopping before convex terrain

15.3.1 Principle

This test measures the distance between a robot and a convex terrain including ascending stairs after performing a protective stop in order to evaluate a protective measure, “travel surface sensing” (see ISO 13482:2014, 5.10.3.3 and 6.5.3).

This test is applicable to robots that are mobile and safety-related travel surface sensing functionality.

This test consists of three steps:

a) setting up,

b) performing test motions, and

c) measuring the distance.

This test uses a travel surface and convex terrain.

15.3.2 Apparatus

a) Test travel surface

A travel surface adapted to the anticipated robot use environment is used. If braking distance differs by surfaces, the surface with the longest braking distance is used.

It is also important to have adequate length and width for the robot to slow down and stop after acceleration to normal travel speed.

b) Convex terrain

The convex terrain is simulated by a block with a flat top and vertical sides. Its height is at least the maximum that the robot can overcome, but not more than 120 % of the maximum. The convex height can be simulated with the use of elevating platform, etc. However, it is necessary to fill the crevice between the travel surface and the convex height (elevating platform) that can be detected by the travel surface sensor. The width of the convex terrain is longer than the full width of the robot.

15.3.3 Procedure

a) The robot travels at a speed that is typical under the intended use conditions.

b) It makes a protective stop when approaching the convex terrain. The approach course is the following:

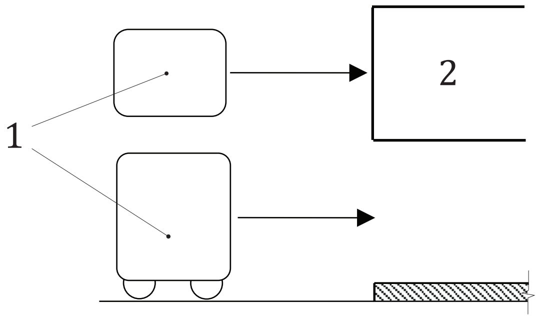
   1) The course in which the robot approaches the centre of the convex width [see Figure 20 a)].

   2) The course in which the line connecting the right end of the convex terrain and the left-most side of the robot affected by the terrain matches the travel direction of the robot [see Figure 20 b)].

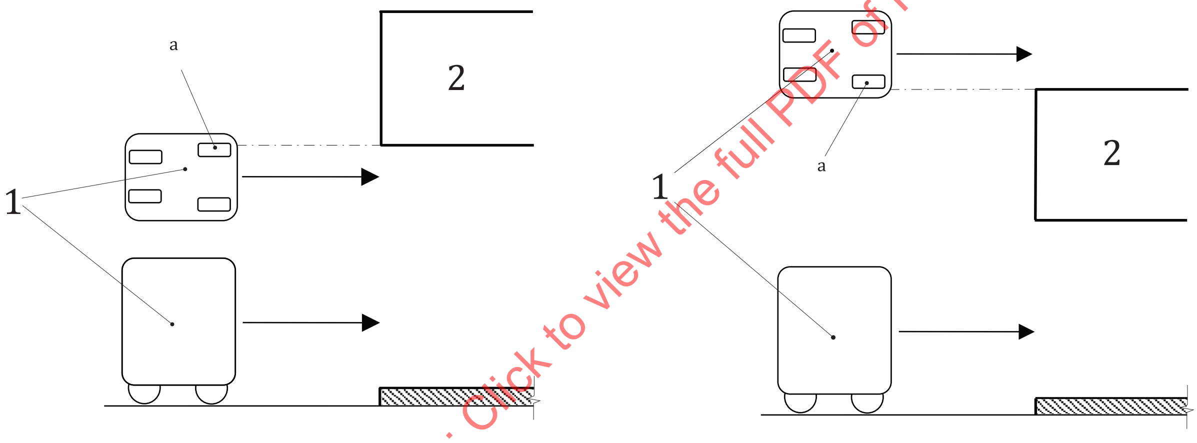
3) The course in which the line connecting the left end of the convex terrain and the right-most side of the robot affected by the terrain matches the travel direction of the robot [see Figure 20 c)].

c) The approach angle is the angle anticipated in the intended use conditions. If this is not specified, the angles are 10°, 45°and 90° to the edge of the convex terrain, with tolerance of ±5° [see Figure 21)].

d) The shortest distance between the edge of the convex terrain and the robot is measured when the robot stops completely.



a) Centre of the terrain and the centre of the robot



b) Right end of the convex and left end of the robot

c) Left end of the convex and right end of the robot

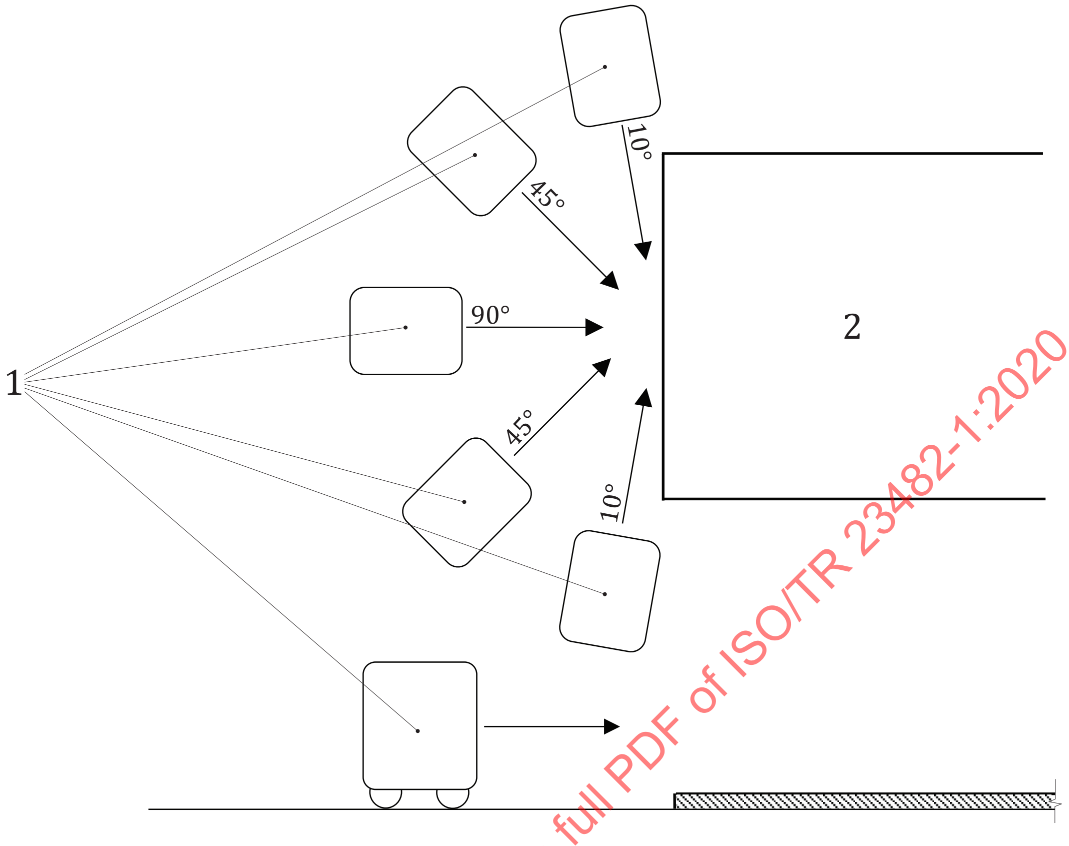
Key

1 robot

2 convex

[a] Farthest point of robot affected by terrain.

Figure 20 — Placement method in relation to convex terrain



Key

1	robot
2	convex

Figure 21 — Approach angle to convex terrain

15.4 Distance of stopping before concave terrain

15.4.1 Principle

This test measures the distance between a robot and concave terrain, including descending stairs after performing a protective stop, in order to evaluate protective measures for “travel surface sensing” (see ISO 13482:2014, 5.10.3.3 and 6.5.3).

This test is applicable to all robots that are mobile and have safety-related travel surface sensing functionality.

This test is implemented using the same method as the test in 15.3, except that the test terrain is the smallest pit in which the travel surface contact area of the robot can fall. Unless appropriate to the robot feature, the test conditions are chosen to fit it.

15.4.2 Apparatus

a) Test travel surface

A travel surface adapted to the anticipated robot use environment is used. If braking distance differs by surface, the surface with the longest braking distance is used.

It is also important to have adequate length and width for the robot to slow down and stop after acceleration to normal travel speed.

b) Concave terrain

The concave depth is deeper than the level that the robot can overcome. The depth can be simulated with the use of elevating platform, etc., so long as it is shaped for the robot to fall into the depression. However, it is necessary to fill the crevice between the test surface and the depth (elevating platform) that can be detected by the travel surface sensor. The width of the concave terrain is greater than the full width of the robot. Where risk assessment shows that shapes of the concave are different from those given in Figure 22 a), then different shapes applied for the test.

15.4.3 Procedure

a) The robot travels at a speed that is typical under the intended use conditions.

b) It makes a protective stop when approaching the concave terrain. The approach course is the following:

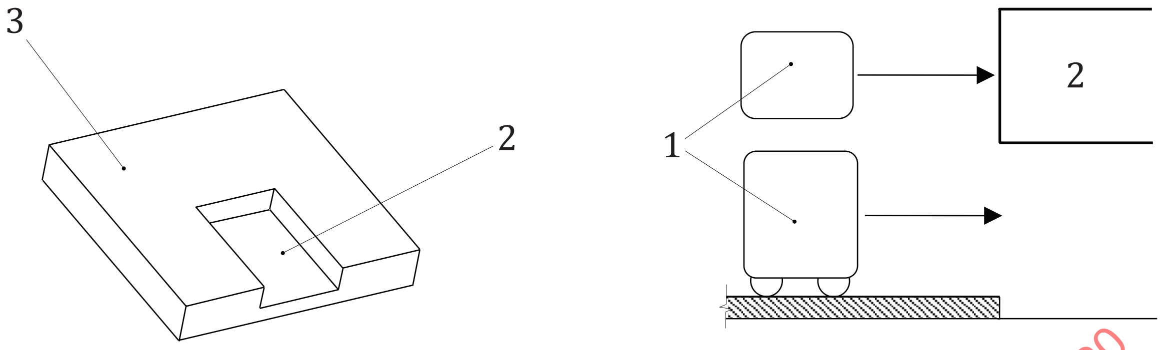
   1) the course in which the robot approaches the centre of the concave width [see Figure 22 b)];

   2) the course in which the line connecting the right end of the concave terrain and the farthest point of the robot left side affected by the terrain matches the travel direction of the robot [see Figure 22 c)];

   3) the course in which the line connecting the left end of the concave terrain and the farthest point of the robot right side affected by the terrain matches the travel direction of the robot [see Figure 22 d)].

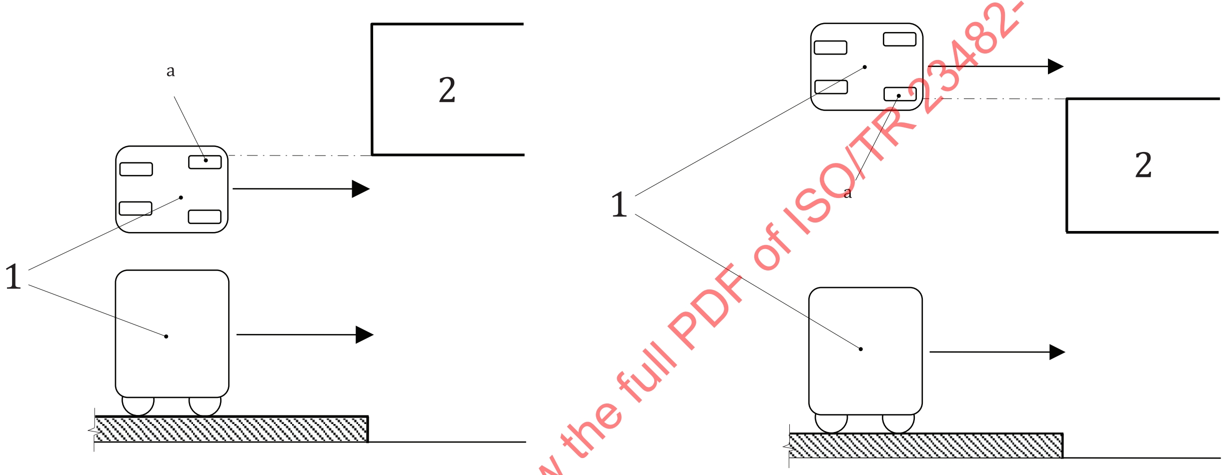
c) If the concave terrain is not rotationally symmetrical, the approach angle is the angle anticipated in the intended use conditions. If this is not specified, the angles are 10°, 45° and 90° to the edge of the concave terrain, with tolerance of ±5° [see Figure 23)].

d) The shortest distance between the edge of the concave terrain and the robot is measured.



a) Example of concave

b) Centre of the concave and the centre of the robot



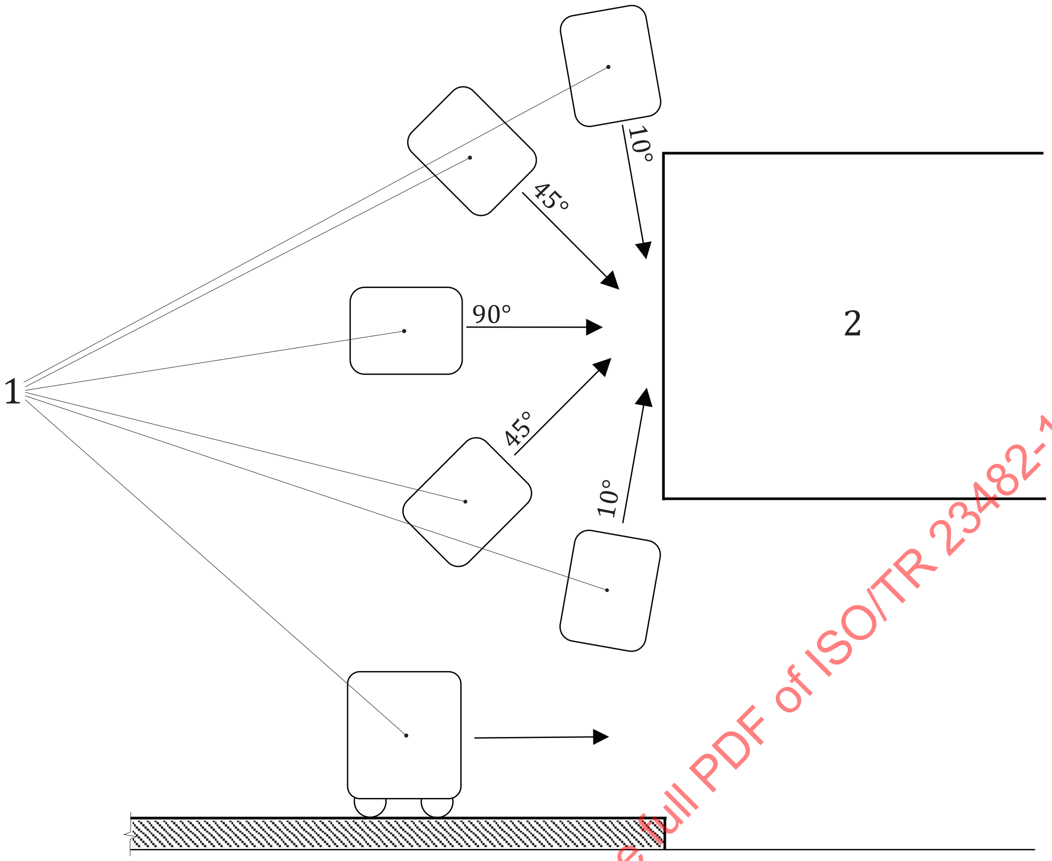
c) Right end of the concave and left end of the robot

d) Left end of the concave and right end of the robot

Key

1	robot
2	concave
3	travel surface
a	Farthest point of robot affected by terrain.

Figure 22 — Placement method in relation to concave terrain



Key

1	robot
2	concave

Figure 23 — Approach angle to concave terrain

16 Test of safety-related localization and navigation

16.1 Principle

The robot travels through an environment while determining its position based on map data and features or markers in the environment. For this test, the geometry of the environment is changed from the geometry stored the internal map. During the test it is monitored if the robot reacts in a hazardous manner on this deviation.

This test is applicable for all mobile robots using an internal map and using markers or features for localization (see ISO 13482:2014, 5.16.2).

16.2 Apparatus

The test environment consists of one rectangular room with a length of 6 m or more and a width of 3 m or more (with respect to the dimensions of the robot being tested). A rectangular obstacle with a length and width of about 1 m is placed near the middle of one of the longer sides of the room (see Figure 24).

One of the shorter walls of the room and the obstacle are movable. If the robot’s localization is based on markers, a sufficiently large number of markers is distributed on the walls and the obstacle for the robot to operate. The walls and the obstacle are sufficiently high to be visible by all sensors of the robot used for localization and to obstruct the external view of premises by these sensors.

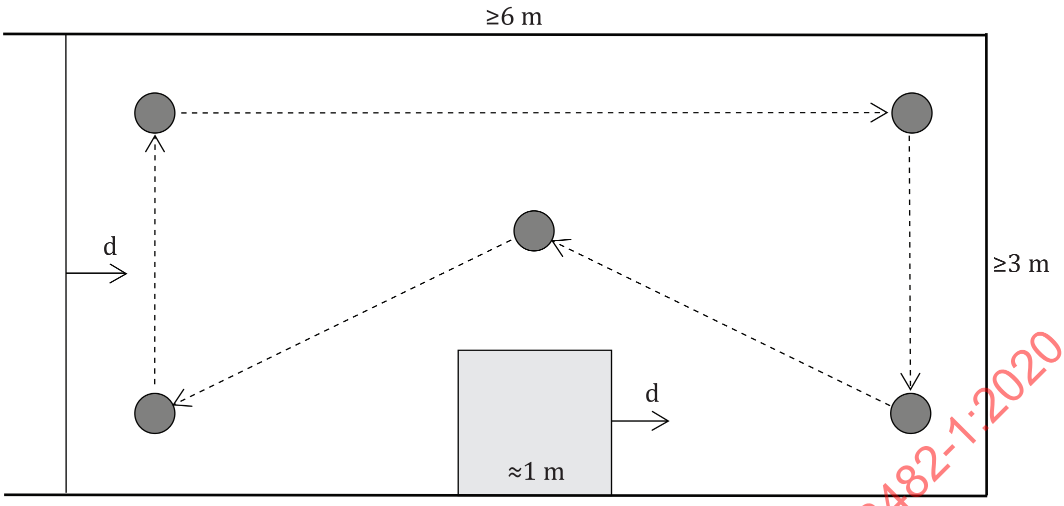


Figure 24 — Apparatus and test path for localization test

16.3 Procedure

The procedure consists of the following steps.

a) A map of the room with the original placement of the wall and the obstacle is generated. This can be performed manually (by providing a map based on the exact room geometry) or by letting the robot generate a map, e.g. with a slam algorithm.

b) The movable wall and the obstacle are moved with a distance d towards the short-fixed wall.

c) The robot is placed in one corner of the room. If necessary, the localization of the robot is initialized so that it is aligned with the nearest corner.

d) The robot is programmed to move along the path indicated in Figure 24. The path is commanded in map coordinates and the via-points are chosen so that the minimum distance to walls and the obstacle equals 150 % of the distance that would cause the robot to execute a protective stop.

The steps c) and d) are performed for displacements of d = 5 cm, d = 10 cm, d = 20 cm and d = 50 cm of the wall and the obstacle. Each test is repeated a minimum of four times for the clockwise direction and a minimum of four times for the counter-clockwise direction.

While the robot travels, it is monitored and recorded if the robot moves jerkily, comes to abrupt unexpected stops or performs other potentially hazardous movements.

17 Test of reliability of autonomous decisions and actions (universal)

17.1 General

If autonomous decisions or actions of a robot cause a hazard, the reliability of decisions and actions needs to be evaluated and a risk assessment needs to be performed to determine if reliability is sufficient (see ISO 13482:2014, 5.12).

Autonomous decisions and actions can include identifying an object, interpreting (ambiguous) user commands, choosing a strategy to minimize expected risks from collisions, etc. Due to the large variety of decision problems, not all problems can be covered by this document.

A test is set up in which a robot is confronted with a situation where autonomous decisions or actions are necessary. The reaction of the robot is measured to determine if decisions and actions were performed correctly. An example for performing object detection tests is outlined in 17.2 and 17.3.

17.2 Object identification

17.2.1 Principle

This test measures the reliability of identifying objects correctly. It is applicable for all robots with an object identification capability.

17.2.2 Apparatus

17.2.2.1 Test objects

A sufficiently large number of test objects which typically occur in intended environments are chosen. If applicable, groups of objects very similar to each other are included.

17.2.2.2 Test facility

Objects are set up in the way that they typically occur in the intended operating environment (e.g. placed on a table, stored in a box or a cupboard, etc.) with typical lighting conditions.

17.2.3 Procedure

The robot identifies each object. The sum of objects identified correctly is recorded. If objects are identified incorrect, the object type and the object that was mistaken for are recorded.

18 Command devices (universal)

18.1 Safe operation in case of connection, disconnection or reconnection of a command device

18.1.1 Principle

This test examines the reaction of the robot on connection, disconnection and reconnection of command devices to make sure that no unacceptable risk occurs in a such situation.

The test is applicable to all robots having command devices.

During a risk assessment, situations need to be identified in which connection, disconnection or reconnection of command devices can lead to a hazardous situation. The test considers:

- different types and number of command devices;
- operational modes, tasks and moving patters in which hazardous reactions can be expected;
- hazardous states in internal control systems;
- different methods of connection or disconnection such as connection by software commands, connection with hardware plugs, power loss and re-initiation of power, as well as destructive ways of disconnection such as ripping off/cutting a cable;
- intended and unintended connection, disconnection and reconnection.

18.1.2 Apparatus

No other apparatus than the robot itself and the relevant command device(s) are needed.

18.1.3 Procedure

a) For each potentially hazardous situation identified during risk assessment, the robot is set up and put into operation according to the operational parameters of the identified situation.

b) The command device in question is connected, disconnected or reconnected according to the operational parameters of the identified situation.

c) For each situation, the robot response to each event is observed and recorded.

18.2 Response to multiple or unintended command devices

18.2.1 Principle

This test determines if a personal care robot is “designed and constructed in such a way that it responds only to signals from the intended control unit(s) (see ISO 13482:2014, 6.9.3).

The test is applicable to all robots having multiple control units.

During a risk assessment, situations need to be identified in which multiple control units are used while only signals from one control unit can be accepted. The test considers:

— different types and number of control units;

— operational modes, tasks and moving patterns in which hazardous reactions can be expected;

— hazardous states in internal control systems.

18.2.2 Apparatus

No other apparatus than the robot itself and the relevant control unit(s) are needed.

18.2.3 Procedure

a) For each potentially hazardous situation identified during risk assessment, the robot is set up and put into operation according to the operational parameters of the identified situation.

b) Signals are sent from an invalid/not intended control unit and it is monitored if the signals affect the robot in any way.

Attributes of control devices and the robot’s respective reactions are recorded.

18.3 Safe operation in case of loss of communication by cableless or detachable command devices

18.3.1 Principle

This test determines if a personal care robot and its command devices are designed in a way that in the case of loss of communication, or when correct control signals are not received, any robot being controlled by such a device executes a protective stop if continuing the task can create an unacceptable risk (see ISO 13482:2014, 6.9.6).

The test is applicable to all robots having cableless or detachable command devices.

During a risk assessment, possible situations where communication can be lost or corrupted are identified, e.g.

— unplugging or switching off a command device;

— loss of (battery) power;

- moving a command device too far away from the robot;
- operation in areas with high interference by other electronic devices;
- failures in hardware or software.

In addition, possible situations in which incorrect signals can be received by the robot's control system are identified.

18.3.2 Apparatus

The robot and the relevant command devices are needed for this test. Depending on the possible situations where a risk assessment identifies loss of communication or corruption, additional apparatus is necessary to simulate a certain situation. Necessary equipment can include:

- an external power supply for the command device which can be switched off to simulate a loss of battery power;
- a transmitter able to simulate electromagnetic interference by other electronic devices;
- a dummy command device that can simulate failures in hardware and software of a command device so that communication is lost or disturbed, or incorrect signals are sent.

18.3.3 Procedure

a) For each potentially hazardous situation identified during risk assessment, the robot is set up and put into operation according to the operational parameters of the identified situation.

b) The loss or corruption of communication or the sending of incorrect signals is simulated and the reaction of the robot is monitored.

Reactions of the robot to given events and test apparatus used are recorded.

19 Test report

All optional test conditions adjusted to the robot design and/or its intended use are clearly recorded.

The test report contains at least the following information:

a) name and address of the testing institution;

b) name and address of the manufacturer of the personal care robot;

c) type of personal care robot and any serial and batch number;

d) description of any equipment fitted to the personal care robot;

e) details of the settings of adjustable parts;

f) size of test dummy used;

g) test results (see Annex D);

h) date of the test;

i) statement that the test methods were used is as described in this document;

j) any comments or observations.

Annex A
(informative)

Information for evaluating test results

A.1 General

The data provided in this annex can be referred to for defining pass/fail criteria for the tests. Depending on the robot design and environment of use, the manufacturer can adopt an allowable value based on the most appropriate standard. The data given in this annex is not listed as mandatory in ISO 13482. The criteria vary depending on the design of a robot or a robotic device and its intended use cases (e.g. materials of a robot part, existence of a child in the intended environments, whether a contact between a human and the robot is intended or not, etc.).

A.2 Acoustic noise (6.2)

The criteria of acoustic noise vary depending on the intended use case. An example is described in IEC 60601-1:2012, 9.6.1 as "The latest research indicates a value of 85 dBA for 8 h over a 24 h period with an offset of 3 dBA when the time doubles or halves."

A.3 Surface temperature (6.3)

A.3.1 General

The criteria of surface temperature vary depending on materials, duration of contact, existence of a child in the intended environments, etc.

A.3.2 Maximum allowable temperatures for medical electrical equipment parts

IEC 60601-1:2012, Clause 11 Table 23 describes the maximum allowable temperatures for medical electrical equipment parts that are likely to be touched by adults only, no matter if intentionally or accidentally. See Table A.1.

Table A.1 — Maximum allowable temperatures specified in IEC 60601-1:2012

Medical electrical equipment parts		Maximum temperature °C		
		Metal and liquids	Glass, porcelain, vitreous material	Moulded material, plastic, rubber, wood
External surfaces of medical electrical equipment that are likely to be touched for a time “t”	$t < 1$ s	74	80	86
	$1 \text{ s} \leq t < 10$ s	56	66	71
	$10 \text{ s} \leq t < 1$ min	51	56	60
	$1 \text{ min} \leq t$	48	48	48

A.3.3 Limit of temperature rise of household and similar electrical appliance

IEC 60335-1:2010, Clause 11 Table 3 describes the temperature rise limit of surfaces of parts of household and similar electrical appliances. The limits described are not the absolute values, but the rise from the ambient temperature which is defined in IEC 60335-1:2010, 5.7.

A.3.4 Maximum allowable temperatures for audio/video, information and communication technology equipment

IEC 60950-1:2005/Amd2:2013, 4.5 Table 4C describes the maximum allowable temperatures for “mains-powered or battery-powered information technology equipment, including electrical business equipment and associated equipment” parts that are likely to be touched, no matter if intentionally or accidentally.

IEC 62368-1:2014, Clause 9 describes a risk analysis and the maximum allowable temperatures for “electrical and electronic equipment within the field of audio, video, information and communication technology, and business and office machines” parts that are likely to be touched, no matter if intentionally or accidentally.

A.3.5 Burn threshold

IEC Guide 117:2010, Annex A and ISO 13732-1:2006, Clause 4 provide burn threshold data.

A.4 Injury criteria in intended contact and unintended contact and collision with a robot (7.1 and 7.2)

A.4.1 Matters to be considered

Injury criteria are determined considering

a) intended use cases, e. g. existence of a child in the intended environments,

b) whether the contact is intended or unintended.

When data in this section are provided as probabilities of injury (see A.4.3.3 and A.4.4.1), proper probability is selected to define criteria for test results. Some examples are described in A.4.5.

Although most of the data are information for the injury criteria in collisions, they are applicable to the criteria of the tests of force control for intended and unintended contacts. The data indicated by parameters other than force are also applicable if the parameters are measured in the tests of the force controls.

A.4.2 Pain onset

ISO/TS 15066:2016, Annex A summarizes informative data of pain onset in quasi static and transient contact (including intended contact) with robots in collaborative operation. Table A.2 reproduces ISO/TS 15066:2016, Table A.2, and provides quantitative maximum values for quasi static and transient contact between persons and the robot system.

NOTE 1 At the time of publication of this document, the pain onset criterion described in ISO/TS 15066 is the only criterion for evaluating forces and impacts by robots that has been standardized, and is considered to be the first source for tolerable pain limits. Where certain use cases or injury types are missing in ISO/TS 15066, other criteria can serve as a reference with care.

NOTE 2 Yamada, et. al., Saito, et. al. and Muttray, et. al. reported pain tolerance values which are associated with the work done by Muttray, et. al.

Table A.2 — Biomechanical limits

Body region	**Specific body area**		**Quasi-static contact**		**Transient contact**	
			Maximum permissible pressure[a] p_s N/cm^2	**Maximum permissible force**[b] N	**Maximum permissible pressure multiplier**[c] P_T	**Maximum permissible force multiplier**[c] F_T
Skull and forehead[d]	*1*	*Middle of forehead*	*130*	*130*	*Not applicable*	*Not applicable*
	2	*Temple*	*110*		*Not applicable*	
Face[d]	*3*	*Masticatory muscle*	*110*	*65*	*Not applicable*	*Not applicable*
Neck	4	Neck muscle	140	150	2	2
	5	Seventh neck muscle	210		2	
Back and shoulders	6	Shoulder joint	160	210	2	2
	7	Fifth lumbar vertebra	210		2	2
Chest	8	Sternum	120	140	2	2
	9	Pectoral muscle	170		2	
Abdomen	10	Abdominal muscle	140	110	2	2
Pelvis	11	Pelvic bone	210	180	2	2
Upper arms and elbow joints	12	Deltoid muscle	190	150	2	2
	13	Humerus	220		2	
Lower arms and wrist joints	14	Radial bone	190	160	2	2
	15	Forearm muscle	180		2	
	16	Arm nerve	180		2	
Hands and fingers	17	Forefinger pad D	300	140	2	2
	18	Forefinger pad ND	270		2	
	19	Forefinger end joint D	280		2	
	20	Forefinger end joint ND	220		2	
	21	Themar eminence	200		2	
	22	Palm D	260		2	
	23	Palm ND	260		2	
	24	Back of the hand D	200		2	
	25	Back of the hand ND	190		2	
Thighs and knees	26	Thigh muscle	250	220	2	2
	27	Kneecap	220		2	
Lower legs	28	Middle of shin	220	130	2	2
	29	Calf muscle	210		2	

Table A.2 *(continued)*

Body region	Specific body area	Quasi-static contact		Transient contact	
		Maximum permissible pressure[a] p_s N/cm^2	Maximum permissible force[b] N	Maximum permissible pressure multiplier[c] P_T	Maximum permissible force multiplier[c] F_T

[a] These biomechanical values are the result of the study conducted by the University of Mainz on pain onset levels. Although this research was performed using state-of-the-art testing techniques, the values shown here are the result of s single study in a subject area that has not been the basis of extensive research. There is anticipation that additional studies will be conducted in the future that can result in modification of these values. testing was conducted using 100 healthy adult test subjects on 29 specific body areas, and for each of the body areas, pressure and force limits for quasi-static contact were established evaluating onset of pain thresholds. The maximum permissible pressure values shown here represent the 75th percentile of the range of recorded values for a specific body area. They are defined as the physical quantity corresponding to when pressures applied to the specific body area create a sensation corresponding to the onset of pain. Peak pressures are based on averages with a resolution size of 1 mm^2. The study results are based on a test apparatus using a flat (1,4 × 1,4) cm (metal) test surface with 2 mm radius on all four edges. there is a possibility that another test apparatus can yield different results. For more details of the study, see ISO 7176-13.

[b] The values for maximum permissible force have been derived from a study carried out by an independent organization (see ISO 7176-21), referring to 188 sources. These values only refer to the body regions, not to the more specific areas. The maximum permissible force is based on the lowest energy transfer criteria that can result in a minor injury, such as a bruise, equivalent to a severity of 1 on the Abbreviated Injury Scale (AIS) established by the Association for the Advancement of Automotive Medicine. Adherence to the limits will prevent the occurrence of skin or soft tissue penetrations that are accompanied by bloody wounds, fractures or other skeletal damage and to the below AIS 1. They will be replaced in future by values from a research more specific for collaborative robots.

[c] The multiplier value for transient contact has been derived based on studies which show that transient limit values can be at least twice as great as quasi-static values for force and pressure. For study details, see ISO 7176-8, ISO 7176-10, ISO 7176-11 and ISO 8373.

[d] Critical zone (*italicized*).

A.4.3 Soft tissue injury tolerance

A.4.3.1 Tangential traction — Time characteristics for blister generation

It is useful to show the samples of values associated with the blister generation which is described in Clause 8, test of physical hazard characteristics. Figure A.1 shows tangential traction, i.e. time characteristics for a cuff in contact with porcine skins in the range of considerably longer time. Tangential traction is measured by use of a rheometer where traction is precisely calculated with the contact area between the load point and the sample surface accurately known. The experimental data obtained using human subjects are compared in the same figure in shorter time, which was conducted by P. F. D. Naylor. In the figure, three exemplar lines are drawn based upon the statistically estimated standard deviation of $2\hat{\sigma}$, $3\hat{\sigma}$, and $4\hat{\sigma}$ after an outlier analysis is made.

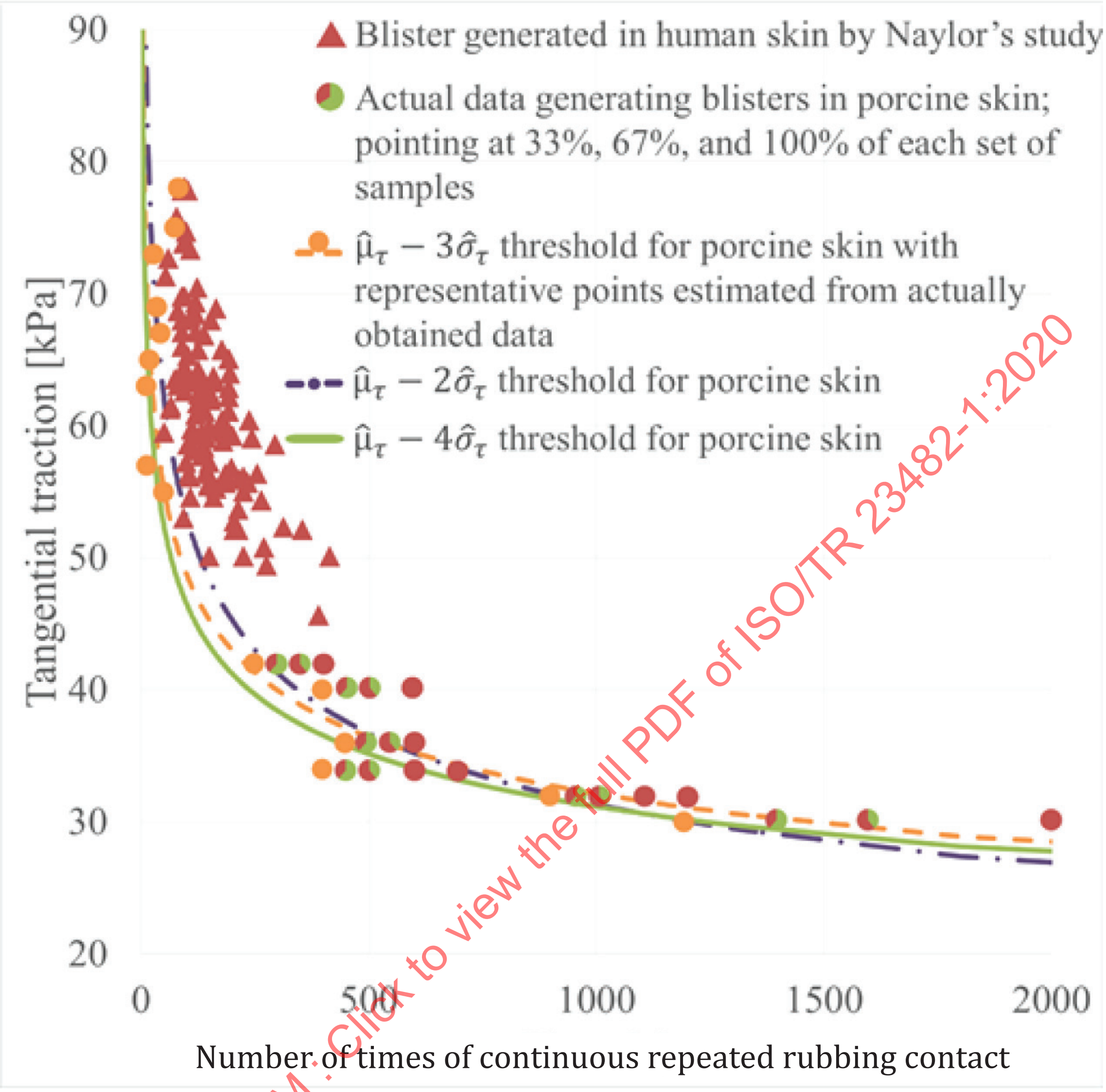
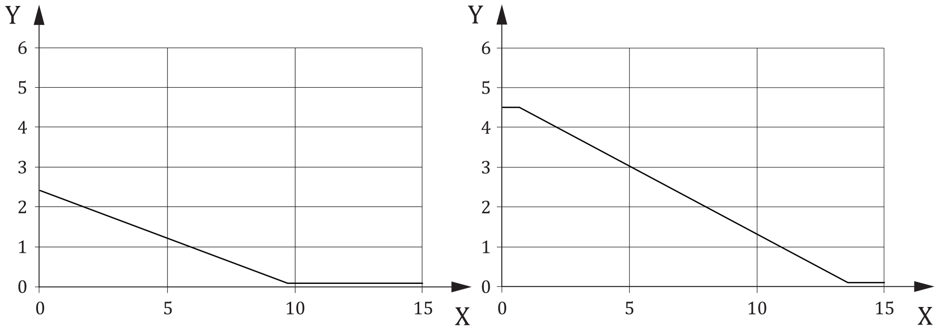
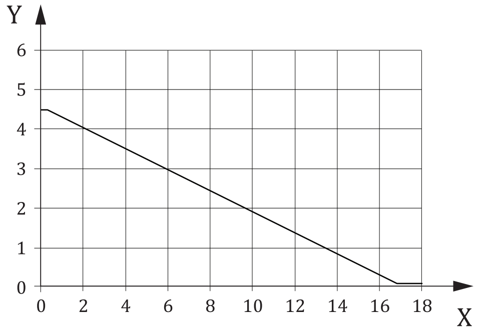


Figure A.1 — Tangential traction: time characteristics for blister generation

A.4.3.2 Mass and velocity of moving parts

Haddadin, et al. provide the critical mass and velocity for soft tissue injury caused by blunt impact (see Figure A.2). To apply these tolerance values to a robot, the impact velocity is measured instead of the impact force in 7.2.





Key

X impactor mass (kg)

Y maximum velocity (m/s)

Figure A.2 — Conservative safety curves for impact by sphere with 5 mm radius (top left), sphere with 12,5 mm radius (top right), and wedge 45° (bottom) for robot real-time control to remain below all observed contusion without skin opening obtained from experiment data by Haddadin, et al.

A.4.3.3 Contact pressure and transferred energy

Fujikawa, et al. provide the probability of soft-tissue injury (bruise) caused by blunt impact by robots as a function of the peak mean contact pressure P_{peak}.

$$\mathrm{Pr}_P = 1/\left\{1+\exp\left(5{,}637 - 2{,}355\, P_{peak}\right)\right\}.$$

To apply the data to a robot, the contact pressure is estimated. The contact pressure is directly measured by pressure sensors applied for the impact force measurement in 7.1 and 7.2. It is also estimated by dividing the peak impact force by contact area supposing the contact pressure in the contact area has approximately a uniform distribution. For measuring these data, two kinds of compliance (i.e. the human soft tissue compliance and the human structure compliance) can be applied to the part impacted by a robot. They decrease the impact force and the contact pressure, and they increase the contact area.

Fujikawa, et al. also provide the probability of soft-tissue injury (bruise) caused by blunt impact by robots as a function of the total energy transferred to human body parts:

$$\mathrm{Pr}_U = 1/\left\{1+\exp\left(9{,}243 - 0{,}068\,6\, U_{total}\right)\right\}.$$

Here, U_{total} is the total transferred energy per unit area as,

$$U_{total} = \frac{1}{A}\int_0^{\delta_1} F d\delta\ .$$

Here, A is the contact area, F is the contact force, δ is the displacement of the robot moving part, and δ_1 is the maximum displacement of the robot part.

To apply the data to a robot, the total transferred energy per unit area is estimated by one of the following methods.

a) The displacement of the robot part during the contact and the contact area are measured as well as the impact force in 7.1 and 7.2, and the total transferred energy per unit area is calculated as it is defined by the formula.

b) The contact area and the velocity of the robot part are measured instead of the impact force in 7.1 and 7.2., and the total transferred energy per unit area is calculated, if the transferred energy is approximated by the kinetic energy of the robot part as,

$$U_{total} = mv^2/2A.$$

Here, *m* is the effective mass of the robot part, and *v* is the velocity of the robot part at the beginning of the contact.

For measuring the data, two kinds of compliance (i.e. the human soft tissue compliance and the human structure compliance) can be applied to the part impacted by a robot. They decrease the impact force, and they increase the displacement and the contact area.

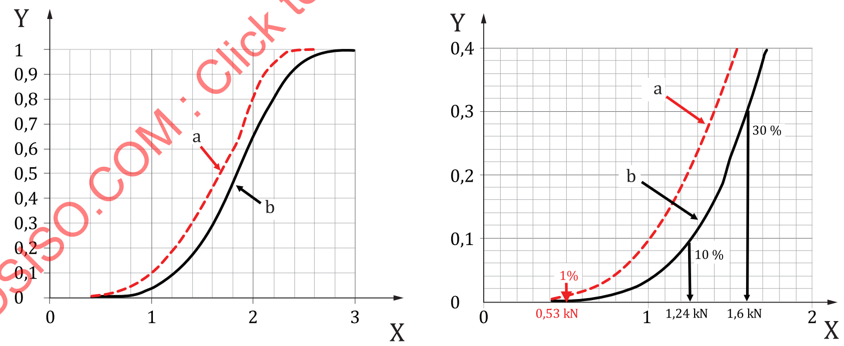
NOTE Injury criteria for a bruise are as follows.

- For the peak mean contact pressure:
  - 30 % probability of soft-tissue injury (bruise): 2,03 MPa;
  - 10 % probability of soft-tissue injury (bruise): 1,46 MPa;
  - 1 % probability of soft-tissue injury (bruise): 0,45 MPa.
- For the total energy.
  - 30 % probability of soft-tissue injury (bruise): 122 kJ/m^2;
  - 10 % probability of soft-tissue injury (bruise): 103 kJ/m^2;
  - 1 % probability of soft-tissue injury (bruise): 67 kJ/m^2.

A.4.4 Injury criteria

A.4.4.1 Foot injury

Fujikawa, et al. provide the probability of the metatarsal fracture of adult females as a function of the load during a run-over incidents (see Figure A.3).



Key

X load on human 4th metatarsal (kN)

Y fracture probability

a 95 percentile confidence bound of Weibull plot.

b Probability obtained from Weibull plot.

Figure A.3 — Predicted cumulative fracture probability of human 4th metatarsal by a robot tyre (average of six typical human females) estimated from experiment data by Fujikawa, et al.

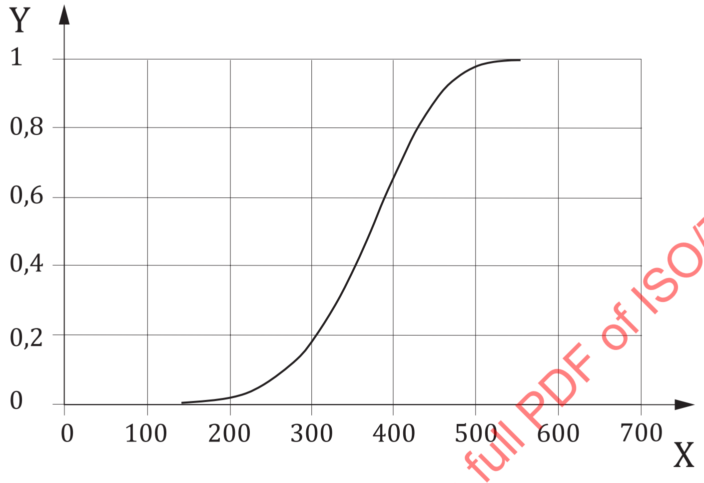
NOTE Injury criteria for foot bone fracture are as follows:

- 30 % probability of the metatarsal fracture: 1,6 kN;
- 10 % probability of the metatarsal fracture: 1,24 kN;

- 1 % probability of the metatarsal fracture: 0,77 kN;
- 1 % probability of the metatarsal fracture with 95 percentile confidence bound 0.53 kN.

A.4.4.2 Leg injury

Takahashi, et al. provide the probability of the tibia fracture of adults as a function of the bending moment in accidents. An example of methods for measuring bending moment is described in the UN Vehicle Regulation No. 127 Annex 5. The flexible lower legform impactor defined in Annex 4 of the regulation is impacted to a car bumper at specified contact conditions. The bending moment is measured by transducers installed in the lower legform impactor. See Figure A.4.



Key

X leg bending moment (Nm)

Y leg fracture probability

Figure A.4 — Probability of the tibia fracture estimated by Takahashi, et al.

A.4.4.3 Head injury

National Highway Traffic Safety Administration (NHTSA) provides the probability of the head injury with AIS 1 level for three-year-old children in accidents. It is provided as a function of Head Injury Criterion (HIC_{15}):

$$HIC_{15}=\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2}a(t)dt\right]^{2.5}(t_2-t_1).$$

where

$a(t)$ is the head acceleration in acceleration of gravity (g);

t_1 and t_2 are the times during the acceleration pulse with 15 ms interval.

Table A.3 — Probability of the head injury with AIS 1 level for three-year-old children as a function of HIC_{15} provided by NHTSA

HIC_{15}	50	100	150	200	250	300	350	400	450	500
Probability of AIS1	18,94 %	40,86 %	53,44 %	59,48 %	61,49 %	61,11 %	59,34 %	56,80 %	53,86 %	50,75 %