PD ISO/TS 15066:2016

BSI Standards Publication

Robots and robotic devices — Collaborative robots

bsi.

...making excellence a habit.™

National foreword

This Published Document is the UK implementation of ISO/TS 15066:2016.

The UK participation in its preparation was entrusted to Technical Committee AMT/-/2, Robots and robotic devices.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

© The British Standards Institution 2016. Published by BSI Standards Limited 2016

ISBN 978 0 580 85344 9

ICS 25.040.30

Compliance with a British Standard cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 March 2016.

Amendments issued since publication

Date	Text affected

TECHNICAL SPECIFICATION

ISO/TS 15066

First edition
2016-02-15

Robots and robotic devices — Collaborative robots

Robots et dispositifs robotiques — Robots coopératifs

Reference number
ISO/TS 15066:2016(E)

© ISO 2016

COPYRIGHT PROTECTED DOCUMENT

© ISO 2016, Published in Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized otherwise in any form or by any means, electronic or mechanical, including photocopying, or posting on the internet or an intranet, without prior written permission. Permission can be requested from either ISO at the address below or ISO's member body in the country of the requester.

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

Contents

Page

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 on 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 the following URL: www.iso.org/iso/foreword.html.

The committee responsible for this document is Technical Committee ISO/TC 299, *Robots and robotic devices*.

This Technical Specification is relevant only in conjunction with the safety requirements for collaborative industrial robot operation described in ISO 10218-1 and ISO 10218-2.

© ISO 2016 – All rights reserved

Introduction

The objective of collaborative robots is to combine the repetitive performance of robots with the individual skills and ability of people. People have an excellent capability for solving imprecise exercises; robots exhibit precision, power and endurance.

To achieve safety, robotic applications traditionally exclude operator access to the operations area while the robot is active. Therefore, a variety of operations requiring human intervention often cannot be automated using robot systems.

This Technical Specification provides guidance for collaborative robot operation where a robot system and people share the same workspace. In such operations, the integrity of the safety-related control system is of major importance, particularly when process parameters such as speed and force are being controlled.

A comprehensive risk assessment is required to assess not only the robot system itself, but also the environment in which it is placed, i.e. the workplace. When implementing applications in which people and robot systems collaborate, ergonomic advantages can also result, e.g. improvements of worker posture.

This Technical Specification supplements and supports the industrial robot safety standards ISO 10218-1 and ISO 10218-2, and provides additional guidance on the identified operational functions for collaborative robots.

The collaborative operations described in this Technical Specification are dependent upon the use of robots meeting the requirements of ISO 10218-1 and their integration meeting the requirements of ISO 10218-2.

NOTE Collaborative operation is a developing field. The values for power and force limiting stated in this Technical Specification are expected to evolve in future editions.

Robots and robotic devices — Collaborative robots

1 Scope

This Technical Specification specifies safety requirements for collaborative industrial robot systems and the work environment, and supplements the requirements and guidance on collaborative industrial robot operation given in ISO 10218-1 and ISO 10218-2.

This Technical Specification applies to industrial robot systems as described in ISO 10218-1 and ISO 10218-2. It does not apply to non-industrial robots, although the safety principles presented can be useful to other areas of robotics.

NOTE This Technical Specification does not apply to collaborative applications designed prior to its publication.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10218-1:2011, *Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots*

ISO 10218-2:2011, *Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration*

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

ISO 13850, *Safety of machinery — Emergency stop function — Principles for design*

ISO 13855, *Safety of machinery — Positioning of safeguards with respect to the approach speeds of parts of the human body*

IEC 60204-1, *Safety of machinery — Electrical equipment of machines — Part 1: General requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10218-1, ISO 10218-2 and ISO 12100 and the following apply.

3.1
collaborative operation
state in which a purposely designed robot system and an operator work within a collaborative workspace

[SOURCE: ISO 10218-1:2011, 3.4, modified]

3.2
power
mechanical power
mechanical rate of doing work, or the amount of energy consumed per unit time

Note 1 to entry: Power does not pertain to the electrical power rating on an electronic device, such as a motor.

© ISO 2016 – All rights reserved

3.3
collaborative workspace
space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation

Note 1 to entry: See Figure 1.

[SOURCE: ISO 10218-1:2011, 3.5, modified]

3.4
quasi-static contact
contact between an operator and part of a robot system, where the operator body part can be clamped between a moving part of a robot system and another fixed or moving part of the robot cell

3.5
transient contact
contact between an operator and part of a robot system, where the operator body part is not clamped and can recoil or retract from the moving part of the robot system

3.6
protective separation distance
shortest permissible distance between any moving hazardous part of the robot system and any human in the collaborative workspace

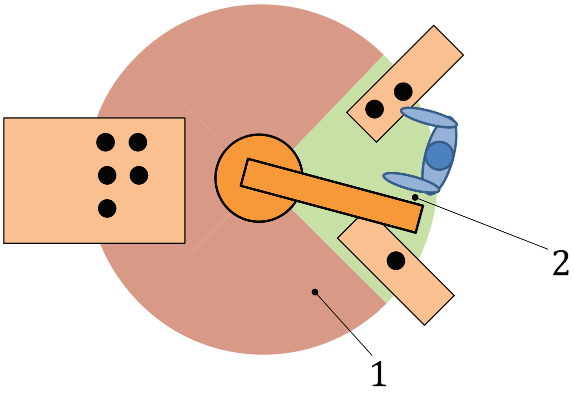
Note 1 to entry: This value can be fixed or variable.

3.7
body model
representation of the human body consisting of individual body segments characterized by biomechanical properties

4 Collaborative industrial robot system design

4.1 General

ISO 10218-2:2011 describes safety requirements for the integration of industrial robots and robot systems, including collaborative robot systems. The operational characteristics of collaborative robot systems are significantly different from those of traditional robot system installations and other machines and equipment. In collaborative robot operations, operators can work in close proximity to the robot system while power to the robot's actuators is available, and physical contact between an operator and the robot system can occur within a collaborative workspace. See Figure 1.



Key

1	operating space
2	collaborative workspace

Figure 1 — Example of a collaborative workspace

Any collaborative robot system design requires protective measures to ensure the operator's safety at all times during collaborative robot operation. A risk assessment is necessary to identify the hazards and estimate the risks associated with a collaborative robot system application so that proper risk reduction measures can be selected.

4.2 Collaborative application design

A key process in the design of the collaborative robot system and the associated cell layout is the elimination of hazards and reduction of risks, and can include or influence the design of the working environment. The following factors shall be taken into consideration:

a) the established limits (three dimensional) of the collaborative workspace;

b) collaborative workspace, access and clearance:

   1) delineation of the restricted space and collaborative workspaces;

   2) influences on the collaborative workspace (e.g. material storage, work flow requirements, obstacles);

   3) the need for clearances around obstacles such as fixtures, equipment and building supports;

   4) accessibility for operators;

   5) the intended and reasonably foreseeable contact(s) between portions of the robot system and an operator;

   6) access routes (e.g. paths taken by operators, material movement to the collaborative workspace);

   7) hazards associated with slips, trips and falls (e.g. cable trays, cables, uneven surfaces, carts);

c) ergonomics and human interface with equipment:

   1) clarity of controls;

   2) possible stress, fatigue, or lack of concentration arising from the collaborative operation;

   3) error or misuse (intentional or unintentional) by operator;

   4) possible reflex behaviour of operator to operation of the robot system and related equipment;

   5) required training level and skills of the operator;

    6) acceptable biomechanical limits under intended operation and reasonably foreseeable misuse;
    7) potential consequences of single or repetitive contacts;

d) use limits:
    1) description of the tasks including the required training and skills of an operator;
    2) identification of persons (groups) with access to the collaborative robot system;
    3) potential intended and unintended contact situations;
    4) restriction of access to authorized operators only;

e) transitions (time limits):
    1) starting and ending of collaborative operation;
    2) transitions from collaborative operations to other types of operation.

4.3 Hazard identification and risk assessment

4.3.1 General

The integrator shall conduct a risk assessment for the collaborative operation as described in ISO 10218-2:2011, 4.3. Special consideration concerning potential intended or reasonably foreseeable unintended contact situations between an operator and the robot system, as well as the expected accessibility of an operator to interact in the collaborative workspace, shall be taken into account.

The user should participate in the risk assessment and design of the workspace. The integrator is responsible for coordinating this participation and for selecting the appropriate robot system components based on the requirements of the application.

4.3.2 Hazard identification

The list of significant hazards for robot and robot systems contained in ISO 10218-2:2011, Annex A, is the result of hazard identification carried out as described in ISO 12100. Additional hazards (e.g. fumes, gases, chemicals and hot materials) can be created by the specific collaborative applications (e.g. welding, assembly, grinding, or milling). These hazards shall be addressed on an individual basis through a risk assessment for the specific collaborative application.

The hazard identification process shall consider the following as a minimum:

a) robot related hazards, including:
    1) robot characteristics (e.g. load, speed, force, momentum, torque, power, geometry, surface shape and material);
    2) quasi-static contact conditions in the robot;
    3) operator location with respect to proximity of the robot (e.g. working under the robot) ;

b) hazards related to the robot system, including:
    1) end-effector and workpiece hazards, including lack of ergonomic design, sharp edges, loss of workpiece, protrusions, working with tool changer;
    2) operator motion and location with respect to positioning of parts, orientation of structures (e.g. fixtures, building supports, walls) and location of hazards on fixtures;
    3) fixture design, clamp placement and operation, other related hazards;

© ISO 2016 – All rights reserved

   4) a determination as to whether contact would be transient or quasi-static, and the parts of the operator’s body that could be affected;

   5) the design and location of any manually controlled robot guiding device (e.g. accessibility, ergonomic, potential misuse, possible confusion from control and status indicators, etc.);

   6) the influence and effects of the surroundings (e.g. where a protective cover has been removed from an adjacent machine, proximity of a laser cutter);

c) application related hazards, including:

   1) process-specific hazards (e.g. temperature, ejected parts, welding splatters);

   2) limitations caused by the required use of personal protective equipment;

   3) deficiency in ergonomic design (e.g. resulting in loss of attention, improper operation).

4.3.3 Task identification

In consultation with the user, the integrator shall identify and document the tasks associated with the robot cell. All reasonably foreseeable task and hazard combinations shall be identified. The collaborative tasks can be characterized by:

a) the frequency and duration of operator presence in the collaborative workspace with a moving robot system (e.g. collaborative assembly with external fixtures);

b) the frequency and duration of contact between an operator and robot system with the drive power or application-related sources of energy active (e.g. hand guiding, physical interaction with tool or workpiece);

c) transitioning between non-collaborative operation and collaborative operation;

d) automatic or manual restart of robot system motion after the collaborative operation has been completed;

e) tasks involving more than one operator;

f) any additional tasks within the collaborative workspace.

4.3.4 Hazard elimination and risk reduction

After hazards are identified, the risks associated with the collaborative robot system shall be assessed before applying risk reduction measures. These measures are based upon these fundamental principles listed in their order of priority (see ISO 10218-2:2011, 4.1.2):

a) the elimination of hazards by inherently safe design or their reduction by substitution;

b) protective measures that prevent personnel from accessing a hazard or control the hazards by bringing them to a safe state (e.g. stopping, limiting forces, limiting speed) before an operator can access or be exposed to the hazards;

c) the provision of supplementary protective measures such as information for use, training, signs, personal protective equipment, etc.

For traditional robot systems, risk reduction is typically achieved through safeguards that separate the operator from the robot system. For collaborative operation, the risk reduction is primarily addressed by the design and application of the robot system and of the collaborative workspace. Specific measures for risk reduction for collaborative operation are identified in Clause 5.

5 Requirements for collaborative robot system applications

5.1 General

Robot systems with collaborative applications shall meet the requirements of ISO 10218-1:2011 and ISO 10218-2:2011. The information contained in this clause supplements that given in ISO 10218-1:2011, 5.10 and ISO 10218-2:2011, 5.11.

5.2 Safety-related control system performance

The safety-related control system functions shall comply with ISO 10218-1:2011, 5.4, or ISO 10218-2:2011, 5.2.

5.3 Design of the collaborative workspace

The design of the collaborative workspace shall be such that the operator can perform all intended tasks. Any risks introduced by machinery or equipment shall be sufficiently mitigated by the measures identified in the risk assessment. The location of equipment and machinery should not introduce additional hazards. Safety-rated soft axis and space limiting, as described in ISO 10218-1:2011, 5.12.3, should be used whenever practicable, to reduce the size of the restricted space.

Risks associated with whole body trapping or crushing between the robot system and, for example, parts of buildings, structures, utilities, other machines, and equipment, shall be eliminated or safely controlled. Clearance in accordance with ISO 10218-2:2011, 5.11.3 should be provided.

NOTE The clearance can be different for systems designed to comply with 5.5.4 and 5.5.5.

If other machines in the collaborative workspace present a hazard, then protective measures shall be applied in accordance with ISO 10218-2:2011, 5.11.2. Any relevant safety-related functions shall comply with the requirements of 5.2.

5.4 Design of the collaborative robot operation

5.4.1 General

The requirements for the design of the collaborative robot operation are provided in ISO 10218-2:2011, 5.11. The operating methods in 5.5 may be used singularly or in combination when designing a collaborative application.

Any detected failure in the safety-related parts of the control system shall result in a protective stop (ISO 10218-2:2011, 5.3.8.3). Operation shall not resume until reset by a deliberate restart action with the operator outside of the collaborative workspace.

5.4.2 Protective measures

All persons within the collaborative workspace shall be protected by protective measures. Safeguards used in a collaborative workspace shall meet the requirements of ISO 10218-2:2011, 5.10.

Information on active settings and configuration of collaborative safety parameters shall be capable of being viewed and documented with a unique identifier (e.g. checksum) so that changes to the configuration can be easily identified (see ISO 10218-1:2011, 5.12.3). Setting and adjusting collaborative safety parameters shall be protected against unauthorized and unintentional changes by password protection or similar security measures.

5.4.3 Stopping functions

During collaborative operation, the operator shall have the means to either stop robot motion at any time by a single action or have an unobstructed means of exiting the collaborative workspace.

Examples of means to stop robot motion can include, but are not limited to:

a) an enabling device;

b) an emergency stop device;

c) stopping the robot by hand, in the case of robots that include this feature.

The number and location of emergency stop devices shall be determined by risk assessment and shall meet the requirements of ISO 13850.

5.4.4 Transitions between non-collaborative operation and collaborative operation

Transitions between methods of collaborative operation or between non-collaborative operation and collaborative operation are particularly critical parts of a collaborative application. These shall be designed such that the robot system shall not pose unacceptable risks to the operator during the transition.

NOTE A visual indicator to identify transitions between collaborative and non-collaborative operations can be used.

5.4.5 Enabling device requirements

ISO 10218-1:2011, 5.8, includes provisions for a pendant control having an enabling device (ISO 10218-1:2011, 5.8.3) and an emergency stop function (ISO 10218-1:2011, 5.8.4). If a risk assessment determines that risk reduction traditionally achieved by the use of an enabling device would be alternatively achieved by inherently safe design measures or safety-rated limiting functions, then the pendant control for a collaborative robot system may be provided without an enabling device.

If a collaborative robot system relying upon safety-rated limiting functions is used without an enabling device, then these functions shall always remain active. The limits (e.g. speed, force, or range) shall be set to a level that provides sufficient risk reduction for programming, setting, troubleshooting, maintenance and other tasks traditionally performed with the use of an enabling device.

Whenever safety-rated limiting functions are not active in the task-specific configuration, the collaborative robot system shall include an alternative protection method, such as an enabling device that meets the requirements of ISO 10218-1:2011, 5.8.3.

When an enabling device is not included with the robot system, the information for use shall include the following:

a) a notification that the enabling device is not included with the robot. If an enabling device is an option, the manufacturer shall provide instructions for how to install the enabling device;

b) a disclaimer stating a robot without an enabling device shall only be used in applications with inherently safe design measures or active safety-rated limiting functions.

5.5 Collaborative operations

5.5.1 General

Collaborative operations may include one or more of the following methods:

a) safety-rated monitored stop;

b) hand guiding;

c) speed and separation monitoring;

d) power and force limiting.

5.5.2 Safety-rated monitored stop

5.5.2.1 Description

In this method, the safety-rated monitored stop robot feature is used to cease robot motion in the collaborative workspace before an operator enters the collaborative workspace to interact with the robot system and complete a task (e.g. loading a part onto the end-effector). If there is no operator in the collaborative workspace, the robot may operate non-collaboratively. When the robot system is in the collaborative workspace, the safety-rated monitored function is active and robot motion is stopped, the operator is permitted to enter the collaborative workspace. Robot system motion can resume without any additional intervention only after the operator has exited the collaborative workspace.

5.5.2.2 Robot requirements

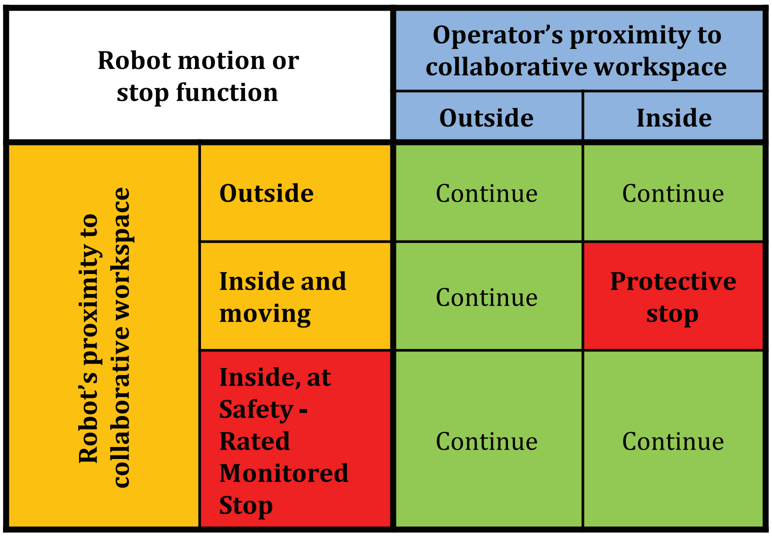
For collaborative operation with safety-rated monitored stop, the following robot system requirements apply:

a) when robot motion is limited, the limits shall comply with ISO 10218-1:2011, 5.12;

b) the robot shall be equipped with the function to achieve a protective stop in accordance with ISO 10218-1:2011, 5.5.3.

5.5.2.3 Robot system requirements

The operations of the safety-rated monitored stop feature are outlined in Figure 2. The robot system is permitted to enter the collaborative workspace only when an operator is not present in the collaborative workspace. If an operator is not present in the collaborative workspace, the robot system may operate non-collaboratively in the collaborative workspace.



Robot motion or stop function		**Operator's proximity to collaborative workspace**	
		Outside	**Inside**
Robot's proximity to collaborative workspace	**Outside**	Continue	Continue
	Inside and moving	Continue	**Protective stop**
	Inside, at Safety - Rated Monitored Stop	Continue	Continue

Figure 2 — Truth table for safety-rated monitored stop operations

The collaborative workspace shall be established with distances that meet the requirements of ISO 13855. The robot system shall be equipped with safety-rated devices which detect the presence of an operator within the collaborative workspace. Access to the restricted space outside the collaborative workspace shall be prevented in accordance with a risk assessment.

When the safety-rated monitored stop feature is used, an operator shall be permitted to enter the collaborative workspace only under the following conditions:

a) when the robot system or other hazards are not present in the collaborative workspace;

© ISO 2016 – All rights reserved

b) when the robot system is in the collaborative workspace and is in a safety-rated monitored stop (stop category 2) in accordance with ISO 10218-1:2011, 5.4 the safety-rated monitored stop shall remain active at all times when an operator is in the collaborative workspace;

c) when the robot system is in the collaborative workspace in a protective stop in accordance with ISO 10218-1:2011, 5.4 and 5.5.3.

In the intended use of this function, the robot may decelerate, resulting in a safety-rated monitored stop (stop category 2) in accordance with IEC 60204-1.

When the operator leaves the collaborative workspace, the safety-rated monitored stop function may be deactivated and robot system motion may resume automatically.

Any condition that violates these operational requirements shall result in a protective stop (stop category 0) in accordance with IEC 60204-1.

5.5.3 Hand guiding

5.5.3.1 Description

In this method of operation, an operator uses a hand-operated device to transmit motion commands to the robot system. Before the operator is permitted to enter the collaborative workspace and conduct the hand-guiding task, the robot achieves a safety-rated monitored stop (see 5.5.2). The task is carried out by manually actuating guiding devices located at or near the robot end-effector.

Robot systems used for hand guiding can be equipped with additional features, such as force amplification, virtual safety zones or tracking technologies.

If the requirements of 5.5.5 are fulfilled in a hand guiding task, then the requirements of 5.5.3 do not apply.

5.5.3.2 Requirements

5.5.3.2.1 General

The robot shall utilize a safety-rated monitored speed function (ISO 10218-1:2011, 5.6.4) and a safety-rated monitored stop function (see 5.5.2). A risk assessment shall be used to determine the safety-rated monitored speed limit. If operator safety is dependent on limiting the range of motion of the robot, the robot shall utilize safety-rated soft axis and space limiting (ISO 10218-1:2011, 5.12.3).

The operating sequence for hand guiding is as follows:

a) the robot system is ready for hand guiding when it enters the collaborative workspace and issues a safety-rated monitored stop (see 5.5.2) — the operator may then enter the collaborative workspace;

b) when the operator has taken control of the robot system with the hand guiding device, the safety-rated monitored stop is cleared and the operator performs the hand guiding task;

c) when the operator releases the guiding device, a safety-rated monitored stop (see 5.5.2) shall be issued;

d) when the operator has exited the collaborative workspace, the robot system may resume non-collaborative operation.

If the operator enters the collaborative workspace before the robot system is ready for hand guiding, a protective stop (ISO 10218-1:2011, 5.5.3) shall be issued.

Access to the restricted space outside the collaborative workspace shall be prevented in accordance with a risk assessment.

5.5.3.2.2 Guiding device

The robot system shall be equipped with a guiding device that incorporates an emergency stop (ISO 10218-1:2011, 5.5.2 and 5.8.4) and an enabling device (ISO 10218-1:2011, 5.8.3), unless the enabling device exclusion requirements of 5.4.5 are met.

The guiding device shall be located considering the following:

a) proximity of operator to robot so as to be able to directly observe robot motion and any hazards that might arise from this motion (e.g. controls mounted on end effector);

b) operator position and posture shall not lead to additional hazards (e.g. operator not under heavy loads or under manipulator arm);

c) operator vantage point shall allow for unobstructed view of entire collaborative workspace (e.g. additional persons entering collaborative workspace).

The mapping between the motion axes of the hand guiding device and the motion axes of the robot shall be clearly presented and easily understood. The direction of motion of the robot and end effector shall be intuitively understandable and controllable from the hand guiding device.

5.5.3.2.3 Transitions between hand guiding and other types of operation

Transitions between hand guiding operations and non-collaborative operation or other types of collaborative operation shall not introduce additional risk. The operator shall control such transitions by deliberate actions (e.g. activating enabling device) and behaviour (e.g. leaving collaborative workspace).

Specific aspects to consider in these cases are:

a) in transitions from hand guiding to the safety-rated monitored stop (see 5.1), the halting of robot motion and the initiation of the safety-rated monitored stop shall not introduce additional hazards;

b) transitions from safety-rated monitored stop to hand guiding shall not lead to unexpected motion;

c) in transitions from hand guiding to non-collaborative operation, all operators shall have exited the collaborative workspace before the robot system can continue with non-collaborative operation;

d) transitions from non-collaborative operation to hand guiding shall not introduce additional hazards.

5.5.3.2.4 Risk assessment

Risk reduction is achieved by the combination of direct control of motion by the operator and appropriate safety-rated limitation of speed and position, as determined by risk assessment. The risk assessment shall specifically take into account:

a) safety-rated monitored speed that allows the operator control of the robot and relevant hazards;

b) the time and distance that is required by the robot to come to a stop upon release of the enabling device or initiation of the protective stop, e.g. for workspace layout with respect to location of operator and obstacles;

c) hazards caused by the workpiece, end effector, peripherals, or application devices.

5.5.4 Speed and separation monitoring

5.5.4.1 Description

In this method of operation, the robot system and operator may move concurrently in the collaborative workspace. Risk reduction is achieved by maintaining at least the protective separation distance between operator and robot at all times. During robot motion, the robot system never gets closer to the operator than the protective separation distance. When the separation distance decreases to a value below the protective separation distance, the robot system stops. When the operator moves away from the robot system, the robot system can resume motion automatically according to the requirements of this clause while maintaining at least the protective separation distance. When the robot system reduces its speed, the protective separation distance decreases correspondingly.

5.5.4.2 Requirements

5.5.4.2.1 General

The robot shall be equipped with a safety-rated monitored speed function (ISO 10218-1:2011, 5.6.4) and a safety-rated monitored stop function (see 5.5.2). If operator safety is dependent on limiting the range of motion of the robot, the robot shall be equipped with safety-rated soft axis and space limiting (ISO 10218-1:2011, 5.12.3). The speed and separation monitoring system shall meet the requirements of 5.2.

Speed and separation monitoring shall apply to all persons within the collaborative workspace. If the performance of the protective measure is limited by the number of persons in the collaborative workspace, the maximum number of persons shall be stated in the information for use. If that maximum value is exceeded, a protective stop shall occur.

If the separation distance between a hazardous part of the robot system and any operator falls below the protective separation distance, then the robot system shall:

a) initiate a protective stop;

b) initiate safety-related functions connected to the robot system in accordance with ISO 10218-2:2011, 5.11.2 g), e.g. turn off any hazardous tools.

The possibilities by which the robot control system can avoid violating the protective separation distance include, but are not limited to:

- speed reduction, possibly followed by a transition to safety-rated monitored stop (see 5.4.1);
- execution of an alternative path which does not violate the protective separation distance, continuing with active speed and separation monitoring.

When the actual separation distance meets or exceeds the protective separation distance, robot motion may be resumed.

5.5.4.2.2 Constant and variable speed and separation values

The maximum permissible speeds and the minimum protective separation distances in an application can be either variable or constant. For variable values, the maximum permissible speeds and the protective separation distances may be adjusted continuously based on the relative speeds and distances of the robot system and the operator. For constant values, the maximum permissible speed and the protective separation distance shall be determined through the risk assessment as worst cases over the entire course of the application.

The means for determining the relative speeds and distances of the operator and robot system shall be safety-rated in accordance with the requirements in ISO 10218-2:2011, 5.2.2.

5.5.4.2.3 Maintaining sufficient separation distance

During automatic operation, the hazardous parts of the robot system shall never get closer to the operator than the protective separation distance. The protective separation distance can be calculated based on the concepts used to create the minimum distance formula in ISO 13855, modified to take into account the following hazards associated with speed and separation monitoring.

a) In constant speed setting situations, the worst-case value for the safety-rated monitored speed of the robot is used. This value depends on the application and is validated by the risk assessment. The constant limit value shall be set as a safety-rated monitored speed according to ISO 10218-1:2011, 5.6.4, to ensure the constant limit is not exceeded.

b) In variable speed setting situations, the speeds of the robot system and of the operator are used to determine the applicable value for the protective separation distance at each instant. Alternatively, the maximum allowed robot speed can be determined based on operator speed and actual separation distance between the robot and operator. The control function to accomplish this shall comply with ISO 10218-2:2011, 5.2.2.

c) The stopping distance of the robot is determined according to ISO 10218-1:2011, Annex B.

The protective separation distance, S_p, can be described by Formula (1):

$$S_\mathrm{p}(t_0) = S_\mathrm{h} + S_\mathrm{r} + S_\mathrm{s} + C + Z_\mathrm{d} + Z_\mathrm{r} \qquad (1)$$

where

$S_\mathrm{p}(t_0)$ is the protective separation distance at time t_0;

t_0 is the present or current time;

S_h is the contribution to the protective separation distance attributable to the operator's change in location;

S_r is the contribution to the protective separation distance attributable to the robot system's reaction time;

S_s is the contribution to the protective separation distance due to the robot system's stopping distance;

C is the intrusion distance, as defined in ISO 13855; this is the distance that a part of the body can intrude into the sensing field before it is detected;

Z_d is the position uncertainty of the operator in the collaborative workspace, as measured by the presence sensing device resulting from the sensing system measurement tolerance;

Z_r is the position uncertainty of the robot system, resulting from the accuracy of the robot position measurement system.

NOTE $S_\mathrm{p}(t_0)$ allows the protective separation distance to be calculated dynamically, allowing the robot speed to vary during the application. $S_\mathrm{p}(t_0)$ can also be used to calculate a fixed value for the protective separation distance, based on worst case values.

Formula (1) applies to all combinations of personnel in the collaborative workspace and moving parts of the robot system. The closest part of the robot and the person in the collaborative workspace could be moving away from each other, while a different part of the robot and the person are approaching each other.

The contribution to the protective separation distance attributable to the operator's change in location, S_h, is expressed by Formula (2):

$$S_\mathrm{h} = \int_{t_0}^{t_0 + T_\mathrm{r} + T_\mathrm{s}} v_\mathrm{h}(t)dt \qquad (2)$$

where

T_r is the reaction time of the robot system, including times required for detection of operator position, processing of this signal, activation of a robot stop, but excluding the time it takes the robot to come to a stop;

T_s is the stopping time of the robot, from the activation of the stop command until the robot has halted; T_s is not a constant, but rather a function of robot configuration, planned motion, speed, end effector and load;

v_h is the directed speed of an operator in the collaborative workspace in the direction of the moving part of the robot, and can be positive or negative depending on whether the separation distance is increasing or decreasing;

t is the integration variable in Formulae (2), (4) and (6).

The quantity S_h represents the contribution to the separation distance due to the operator's motion from the current time until the robot has stopped. Here, v_h is a function of time, and can vary due to either the person's speed or direction changing. The system shall be designed to account for v_h varying in the manner that reduces the separation distance the most. If the person's speed is not being monitored, the system design shall assume that v_h is 1,6 m/s in the direction that reduces the separation distance the most. According to ISO 13855 and IEC/TS 62046:2008, 4.4.2.3, v_h may be a value other than 1,6 m/s depending on a risk assessment.

A constant value for S_h using the estimated human speed (1,6 m/s), expressed in m/s, can be estimated using Formula (3):

$$S_h = 1{,}6 \times (T_r + T_s) \tag{3}$$

The contribution to the protective separation distance attributable to the robot system's reaction time, S_r, is expressed by Formula (4):

$$S_r = \int_{t_0}^{t_0+T_r} v_r(t)dt \tag{4}$$

where v_r is the directed speed of the robot in the direction of an operator in the collaborative workspace, and can be positive or negative depending on whether the separation distance is increasing or decreasing.

The quantity S_r represents the contribution to the separation distance due to the robot's motion upon the person entering the sensing field up to the control system activating a stop. Here, v_r is a function of time, and can vary due to either the robot's speed or direction changing. The system shall be designed to account for v_r varying in the manner that reduces the separation distance the most:

— if the robot's speed is not being monitored, the system design shall assume that v_r is the maximum speed of the robot;

— if the robot's speed is being monitored, the system design may use the current speed of the robot, but shall account for the acceleration capability of the robot in the manner that reduces the separation distance the most;

— if a safety-rated speed limit is in effect, the system design may use this speed limit if the limit is applicable to the part of the robot under consideration.

NOTE A safety-rated speed limit that only monitors the Cartesian speed of the robot TCP does not monitor other parts of the robot that might pose hazards to the operator. A safety-rated speed limit that monitors joint speeds might also be needed.

A constant value for S_r can be estimated using Formula (5):

$$S_r = v_r(t_0) \times T_r \tag{5}$$

The contribution to the protective separation distance that occurs while the robot system is stopping is expressed using Formula (6):

$$S_s = \int_{t_0+T_r}^{t_0+T_r+T_s} v_s(t)dt \tag{6}$$

where v_s is the speed of the robot in the course of stopping, from the activation of the stop command until the robot has halted.

The quantity S_s represents the contribution to the separation distance due to the robot's motion during robot stopping. Here, v_s is a function of time and can vary due to either the robot's speed or direction changing. The system shall be designed to account for v_s varying in the manner that reduces the separation distance the most:

a) if the robot's speed is not being monitored, the system design shall assume that this integral is the robot's stopping distance in the direction that reduces the separation distance the most;

b) if the robot's speed is being monitored, the system design may use the robot's stopping distance from that speed, applied in the direction that reduces the separation distance the most.

Values for S_s should be obtained from the data provided in accordance with ISO 10218-1:2011, Annex B.

The various contributions to the protective separation distance are illustrated in Figure 3. In the top plot of Figure 3, the speed of the operator toward the robot (v_h) is shown as a positive value, while the speed of the robot toward the operator (v_r, v_s) is shown as a negative value.

Alternative implementations are permitted if they achieve the requirements of 5.5.4.2.

© ISO 2016 – All rights reserved

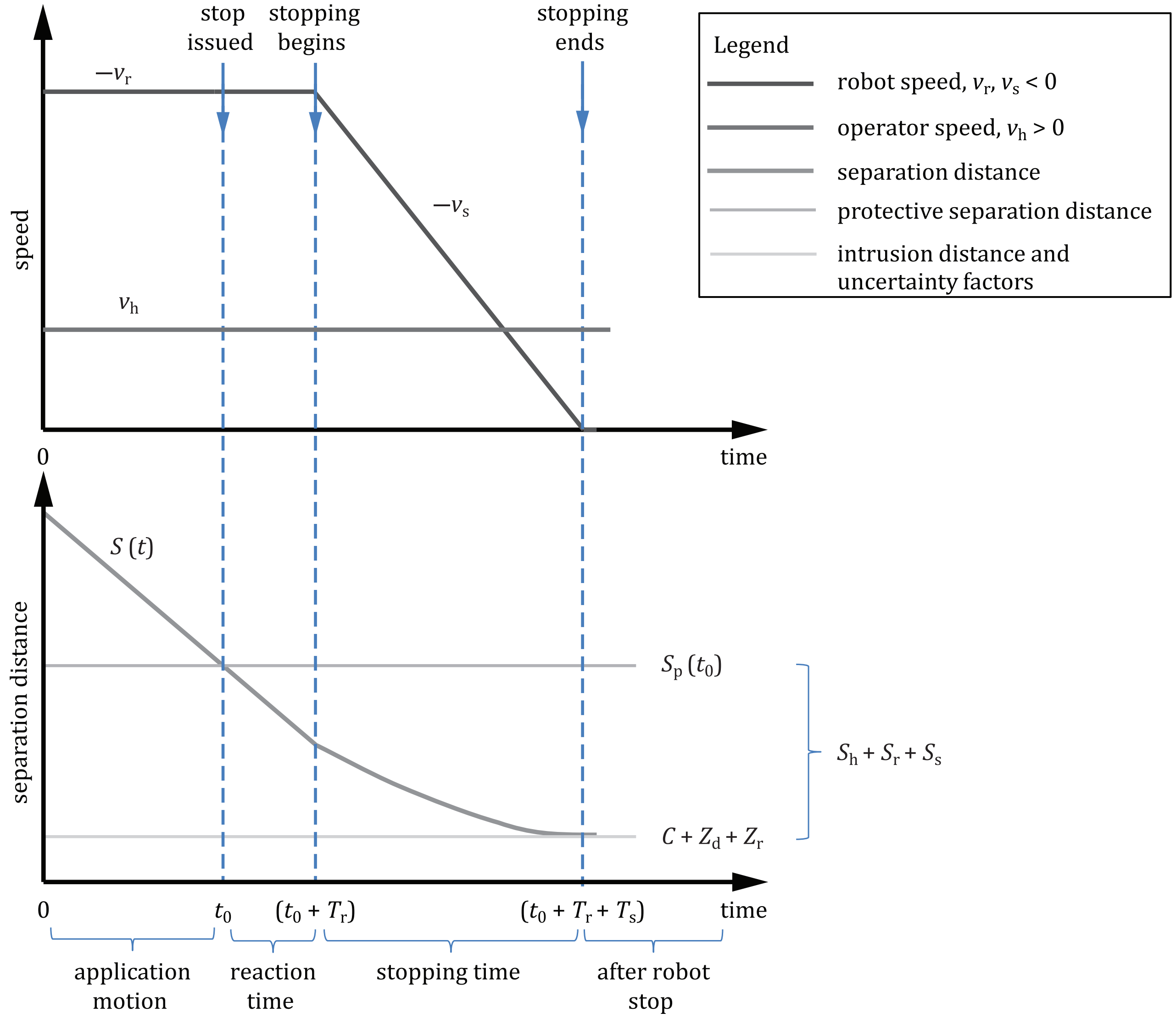


Figure 3 — Graphical representation of the contributions to the protective separation distance between an operator and a robot

5.5.5 Power and force limiting

5.5.5.1 Description

In this method of operation, physical contact between the robot system (including the workpiece) and an operator can occur either intentionally or unintentionally. Power and force limited collaborative operation requires robot systems specifically designed for this particular type of operation. Risk reduction is achieved, either through inherently safe means in the robot or through a safety-related control system, by keeping hazards associated with the robot system below threshold limit values that are determined during the risk assessment. A means to establish the threshold limits values is outlined in Annex A.

5.5.5.2 Contact situations

During collaborative operation using power and force limiting, contact events between the collaborative robot and body parts of the operator could come about in a number of ways:

a) intended contact situations that are part of the application sequence;

b) incidental contact situations, which can be a consequence of not following working procedures, but without a technical failure;

c) failure modes that lead to contact situations..

Possible types of contact between moving parts of the robot system and areas on a person's body are categorized in the following manner.

- Quasi-static contact: This includes clamping or crushing situations in which a person's body part is trapped between a moving part of the robot system and another fixed or moving part of the work cell. In such a situation, the robot system would apply a pressure or force to the trapped body part for an extended time interval until the condition can be alleviated.
- Transient contact: This is also referred to as "dynamic impact" and describes a situation in which a person's body part is impacted by a moving part of the robot system and can recoil or retract from the robot without clamping or trapping the contacted body area, thus making for a short duration of the actual contact. Transient contact is dependent on the combination of the inertia of the robot (see Note 1), the inertia of the person's body part (see Annex A), and the relative speed of the two.

NOTE 1 The relevant inertia of the robot is the moving mass as computed at the contact location. This might be anywhere along the length of the kinematic chain (i.e. the manipulator arm, linkages, tooling and workpiece), so estimating this value makes use of the specific robot pose, link speeds, mass distribution and contact location or uses a worst case value.

NOTE 2 The inertia of human body parts is addressed in reference documents listed in the Bibliography.

5.5.5.3 Risk reduction for potential contact between robot and operator

Risk reduction shall consider means by which possible contact between the operator and robot system would not result in harm to the operator. This is achieved by:

a) identifying conditions in which such contact would occur;

b) evaluating the risk potential for such contacts;

c) designing the robot system and collaborative workspace so that such contact is infrequent and avoidable;

d) applying risk reduction measures to keep the contact situations below threshold limit values.

For the purposes of risk assessment, any such potential contact should consider that the operator is not protected by any risk reduction measures, including personal protective equipment. This identification shall consider the following criteria for potential contact events:

- exposed operator body regions;
- origin of contact events, i.e. intentional action as part of intended use vs. unintentional contact or reasonably foreseeable misuse;
- probability or frequency of occurrence;
- type of contact event, i.e. quasi-static or transient;
- contact areas, speeds, forces, pressures, momentum, mechanical power, energy and other quantities characterizing the physical contact event.

Objects with sharp, pointed, shearing or cutting edges, such as needles, shears, or knives, and parts which could cause injury shall not be present in the contact area.

NOTE 1 Suitable housings, covers or separating planes can be used to mitigate potential hazards.

NOTE 2 There can be other hazards besides contact, including process hazards.

Contact exposure to sensitive body regions, including the skull, forehead, larynx, eyes, ears or face shall be prevented whenever reasonably practicable.

5.5.5.4 Passive and active risk reduction measures

Risk reduction measures to address the quasi-static contact and transient contact are either passive or active in nature. Passive safety design measures address the mechanical design of the robot system, whereas active safety design measures address the control design of the robot system.

Passive safety design methods include, but are not limited to:

a) increasing the contact surface area:
   1) rounded edges and corners;
   2) smooth surfaces;
   3) compliant surfaces;
b) absorbing energy, extending energy transfer time, or reducing impact forces:
   1) padding, cushioning;
   2) deformable components;
   3) compliant joints or links;
c) limiting moving masses.

Active safety design methods include, but are not limited to:

- limiting forces or torques;
- limiting velocities of moving parts;
- limiting momentum, mechanical power or energy as a function of masses and velocities;
- use of safety-rated soft axis and space limiting function;
- use of safety-rated monitored stop function;
- use of sensing to anticipate or detect contact (e.g. proximity or contact detection to reduce quasi-static forces).

The application of these and other related measures shall address the expected exposure of the operator, as determined by a risk assessment.

NOTE A combination of safety functions can be required, e.g. the force limiting safety function can be effective only up to a certain speed limit. In such a case, an additional speed limiting safety function would be necessary.

In the event that one or a combination of passive or active risk reduction measures do not adequately reduce risk, the use of other risk reduction measures, including guards or safeguarding, may be required.

Any clamping event between the collaborative robot system and human body regions shall occur in a way such that the person shall be able to escape independently and easily from the clamping condition.

5.5.5.5 Power and force control limits

The robot system shall be designed to adequately reduce risks to an operator by not exceeding the applicable threshold limit values for quasi-static and transient contacts, as defined by the risk assessment. Annex A provides information on how threshold limit values can be determined.

Robots supporting collaborative operation with power and force limiting can be supplied with means to configure limiting thresholds, e.g. on forces, torques, velocities, momentum, mechanical power, axis ranges or space ranges. Risk reduction associated with transient contact could involve limiting the speed of moving parts (such as the robot, tooling, or workpiece) and an appropriate design of the physical characteristics such as the surface area of the moving part that could contact the operator. Risk reduction associated with quasi-static could include speed limits and physical characteristics, similar to transient contact, plus design characteristics of the parts of the robot system that involve the possible trapping or clamping of an operator or body area.

The limit values for the relevant contact events on the exposed body regions shall be analysed for the most stringent limits. These “worst case” threshold limit values for the transient and quasi-static events shall be used in determining the proper level of risk reduction. Design or measures shall be implemented so that the effects of the identified contacts remain below these threshold limit values.

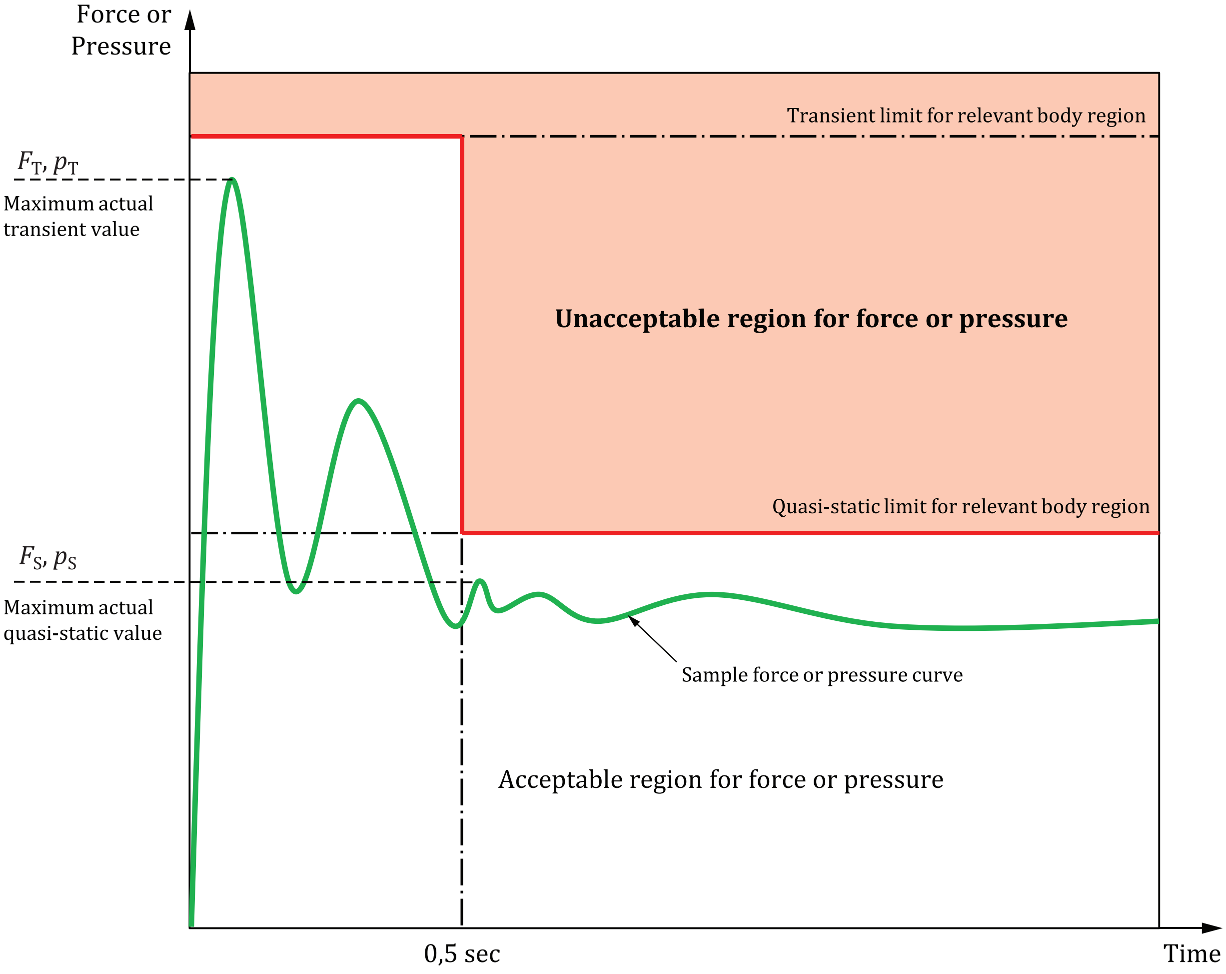


Figure 4 — Graphical representation of acceptable and unacceptable forces or pressures

If robot motion can result in clamping or pinning a body area between a part of the robot and another item in the robot cell, the robot speed shall be limited so that the robot system is able to comply with the protective limits associated with the exposed body area, as shown in Figure 4. The robot shall also be equipped with a means for the operator to manually extricate the body area.

Ergonomic limits can be different from the biomechanical limits. For frequent contacts or other special cases, the applicable threshold limit values can be further reduced to an ergonomically acceptable level.

© ISO 2016 – All rights reserved

5.5.5.6 Speed limits

To reduce the risk associated with transient contacts, the robot system shall limit the speed of moving robot system parts. The speed limits depend on the inertia (mass) and the minimum size of the area on the robot that can contact the exposed body region. Guidance on how speed limits can be established is provided in Annex A.

6 Verification and validation

See ISO 10218-2:2011, Clause 6, for verification and validation requirements.

7 Information for use

7.1 General

See ISO 10218-1:2011, Clause 7, and ISO 10218-2:2011, Clause 7, for information for use requirements.

7.2 Information specific to collaborative robot operations

The documentation that accompanies a collaborative robot system is directed toward a specific collaborative application. The integrator shall provide the user with the necessary information for use of the collaborative system. The integrator shall include in the information for use the safeguards and mode selection required for collaboration operation. The integrator shall provide the following information on system design in addition to requirements in ISO 10218-2:2011, Clause 7:

a) manufacturer or integrator (if an integrator designed the collaborative robot system);

b) testing organization (if testing was conducted);

c) type of robot and brief description of the collaborative application;

d) description of the workplace application (name of workplace including collaborative robot).

7.3 Description of the collaborative robot system

The following documents shall be maintained:

a) specification data for using the collaborative robot in the application (descriptions, drawings and pictures);

b) description and specification data for the safeguards applied to the collaborative workspace and the entire workplace and the collaborative robot system;

c) description of controls for selecting and deselecting relevant types of collaborative operation.

7.4 Description of the workplace application

The following documents shall be provided:

a) description of spatial environmental conditions, entries, exits, traffic routes;

b) description of equipment, installations, machines, optional pieces of equipment, tools and production goods found in the work area that are relevant to the application and their positioning, including that of the robot system;

c) detailed drawings and pictures.

7.5 Description of the work task

The following information shall be documented:

a) description of all the operator's relevant work activities or operations;

b) description of the collaborative robot system's relevant work activities or operations;

c) specification of the chronological sequence of all work activities, especially those within the collaborative workspace;

d) documentation of hazardous robot-to-person distance measurements in all work phases;

e) a description or drawing of the collaborative workspace.

7.6 Information specific to power and force limiting applications

For robot systems meeting the requirements of 5.5.5 by following the guidance in Annex A, the following requirements shall be documented:

a) information specific to the robot, tooling and workpiece (see A.3.6), including:

    1) the effective payload (m_L);

    2) the total mass of the moving parts of the robot (M);

b) anticipated and reasonably foreseeable contact situations between the robot system and the operator, including:

    1) the specific body area(s) that could be contacted (see Table A.1);

    2) a declaration as to whether the contact is transient or quasi-static;

    3) the anticipated surface area or geometric conditions associated with the contact surfaces;

    4) the maximum permissible biomechanical limit(s) associated with the contact (see Table A.2);

c) the proposed risk reduction measures selected:

    1) active or passive risk reduction measures recommended (see 5.5.5.4);

    2) if safety-rated speed control is used, the safety-rated speed limit value shall be documented (see A.3.6).

For robot systems meeting the requirements of 5.5.5 using methods that differ from the guidance in Annex A, the information for use shall include relevant data and information used to establish the power and force limiting function.

Annex A
(informative)

Limits for quasi-static and transient contact

A.1 General

ISO 10218-2:2011, 5.11.5.5, requires that parameters of power, force, and ergonomics pertaining to power and force limited robot systems be determined by a risk assessment. Information on the design of the collaborative robot system is provided in 5.4.4.

This annex provides guidance on how to establish threshold limit values on the collaborative robot system, particularly on power and force limiting applications. The underlying premise behind this guidance is that limits on the collaborative robot system can be calculated based on pain sensitivity thresholds at the human-machine interface in situations where such contact occurs. These threshold limit values can be used to establish pressure and force limit values for various body areas using a body model. This data can then be extrapolated to set energy transfer limits at the human/machine interface. Speed limits can then be prescribed for a robot moving through a collaborative workspace. The speed limit values would maintain force and pressure values below the pain sensitivity threshold if contact with an operator and a robot were to occur.

The limit values in this annex are based on conservative estimates and scientific research on pain sensation.

The guidance in this annex is intended as an informative means to outline a method by which integrators can set limits in power and force limiting applications.

A.2 Body model

A premise of a risk assessment for power and force limited collaborative robot applications is that incidental contact between parts of the collaborative robot system and operator can occur.

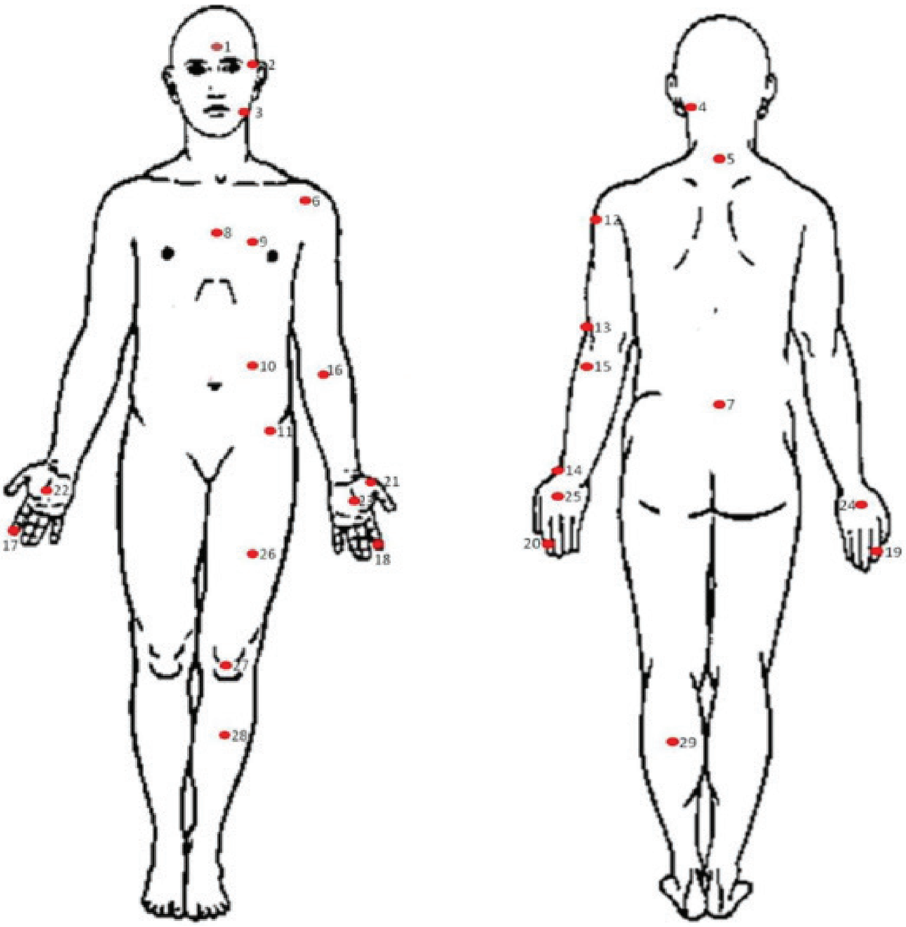
An initial consideration in the risk assessment is to determine where on the operator's body such contact between the robot and operator is likely to occur. This is critical since different body areas will have different thresholds for withstanding biomechanical load without incurring minor injury.

For the purposes of this specification, a body model including 29 specific body areas categorized in 12 body regions has been created. Figure A.1 shows the contact areas in the body model, while Table A.1 shows the specific body regions, classified into general body regions, and designated as being located in either the front or the back of the body.

A.3 Biomechanical limits

A.3.1 General

Biomechanical limits are set forth to prevent biomechanical load initiated by robot motion to create a potential for minor injury to an operator in the event of contact between the operator and the robot.



Front **Rear**

Figure A.1 — Body model

These pressure values can be used to estimate transient pressure and force limits using conservative estimates established by studies (see References [2], [3], [4] and [7]). The transfer energy resulting from hypothetical contact between a robot and human can then be modelled, assuming fully inelastic contact between the robot and the operator, and taking into account the payload capacity of the robot and factors associated with the operator's body part undergoing contact. Once the transfer energy is established, speed limit recommendations for robot motion in the collaborative workspace can be established to maintain the transfer energy at a level below a threshold of minor injury to a human in the event of contact between the robot and operator in the collaborative workspace.

A.3.2 Maximum pressure and force values

Table A.2 provides quantitative maximum values for quasi static and transient contact between persons and the robot system.

The contact data in Table A.2 does not reflect any use of personal protective equipment or anything other than clothing typical of any working environment.

© ISO 2016 – All rights reserved

Although Table A.2 provides data for contact with face, skull and forehead, contact with these areas is not permissible. See 5.5.5.3.

Table A.1 — Body model descriptions

Body region	Specific body area		Front/Rear
Skull and forehead	1	Middle of forehead	Front
	2	Temple	Front
Face	3	Masticatory muscle	Front
Neck	4	Neck muscle	Rear
	5	Seventh neck vertebra	Rear
Back and shoulders	6	Shoulder joint	Front
	7	Fifth lumbar vertebra	Rear
Chest	8	Sternum	Front
	9	Pectoral muscle	Front
Abdomen	10	Abdominal muscle	Front
Pelvis	11	Pelvic bone	Front
Upper arms and elbow joints	12	Deltoid muscle	Rear
	13	Humerus	Rear
Lower arms and wrist joints	14	Radial bone	Rear
	15	Forearm muscle	Rear
	16	Arm nerve	Front
Hands and fingers	17	Forefinger pad D [a]	Front
	18	Forefinger pad ND [a]	Front
	19	Forefinger end joint D [a]	Rear
	20	Forefinger end joint ND [a]	Rear
	21	Thenar eminence	Front
	22	Palm D [a]	Front
	23	Palm ND [a]	Front
	24	Back of the hand D [a]	Rear
	25	Back of the hand ND [a]	Rear
Thighs and knees	26	Thigh muscle	Front
	27	Kneecap	Front
Lower legs	28	Middle of shin	Front
	29	Calf muscle	Rear

[a] D = dominant body side; ND = non-dominant body side.

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	

[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 a 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 could 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 could yield different results. For more details of the study, see Reference [5].

[b] The values for maximum permissible force have been derived from a study carried out by an independent organization (see Reference [6]), referring to 188 sources. These values refer only to the body regions, not to the more specific areas. The maximum permissible force is based on the lowest energy transfer criteria that could 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 be 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 References [2], [3], [4] and [7].

[d] Critical zone (*italicized*)

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
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	Thenar 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	

[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 a 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 could 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 could yield different results. For more details of the study, see Reference [5].

[b] The values for maximum permissible force have been derived from a study carried out by an independent organization (see Reference [6]), referring to 188 sources. These values refer only to the body regions, not to the more specific areas. The maximum permissible force is based on the lowest energy transfer criteria that could 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 be 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 References [2], [3], [4] and [7].

[d] Critical zone (*italicized*)

A.3.3 Relationship between pressure and force

For the purposes of evaluating the contact scenario for a collaborative robot risk assessment, both the force and pressure values need to be calculated and considered.

EXAMPLE 1 In the event of an operator intruding into the tool area of a running robot system, the hands could be clamped by parts of the tool or workpiece. The resulting force value could be well below the force threshold limit value. In such a case, the pressure limit would likely be the limiting factor.

EXAMPLE 2 In the event of contact with a body region with a padded machine surface with a relatively large surface area or a body region with a higher proportion of soft tissue (such as the abdomen), the resulting pressure value could be well below the pressure threshold limit value. In such a case, the force limit would likely be the limiting factor.

In order to reduce the potential for high pressure applied to the operator, the robot system, including the workpiece, should have as high a surface area as possible. Additional padding can increase the surface area which can result in lower pressure.

Contact between rigid robot system parts and human body parts can lead to a non-uniform pressure distribution (pressure peaks) over the contact surface. Under such circumstances, the peak pressure occurring on the contact area is relevant.

The pressure and force limits given by this Technical Specification are not restricted to a specific surface or edge curve. See 5.5.5.3 for restrictions on collaborative robot system parts having sharp edges such as knifes or needles.

A.3.4 Relationship between biomechanical limits and transfer energy during transient contact

The values in Table A.2 can be used to validate the performance of a collaborative robot system during quasi-static contact situations using measurement devices on the robot system.

If the collaborative task involves transient contact, the contact scenario can be modelled using the procedure outlined in this subclause. This modelling is based on the notion that for a given contact scenario between a robot and operator, the body contact region and the contact area are known, and the energy transfer can be modified by adjusting the robot velocity at the point of contact.

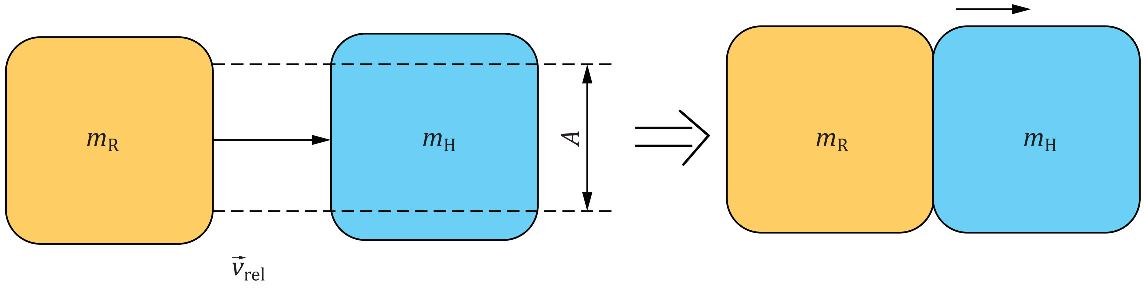
In order to describe this contact scenario, a simple two-body model as outlined in Figure A.2 is used. In the model, the effective mass of the robot, m_R, is moving to come into contact with the effective mass of the human body region, m_H, at a relative vector velocity, v_{rel}, across a two-dimensional surface area, A, resulting in an assumed fully inelastic contact situation, which corresponds to a worst case assumption. The relative kinetic energy is assumed to be fully deposited in the affected body region.

For the purposes of the contact model, m_R can be conservatively estimated as a function of the payload capacity of the robot system (including the workpiece) and the mass of the moving parts of the robot; m_H can be estimated as a function of the actual mass of the body region and the effects of the body region being connected to other body regions. These computations are described in detail in this annex.

For modelling purposes, the effective masses and the spring constants used to represent the human body regions are shown in Table A.3. The body spring constant values are higher in body regions with a higher proportion of soft tissue, which can deform and absorb contacts.

NOTE The quoted spring constants are valid for contact areas of approximately 1 cm^2.

The effective mass values represent a combination of the mass of the body region along with the effects of interconnectivity of the body region with adjacent body regions, particularly as it relates to the body region’s ability to move in the same vector direction of the contact when contact occurs.



Key

A	area of contact between robot and body region
m_H	effective mass of human body region
m_R	effective mass of robot as a function of robot posture and motion
v_{rel}	relative speed between robot and human body region

Figure A.2 — Contact model for transient contact

Table A.3 — Effective masses and spring constants for the body model

Body region	**Effective spring constant** K N/mm	**Effective mass** m_H kg
Skull and forehead	150	4,4
Face	75	4,4
Neck	50	1,2
Back and shoulders	35	40
Chest	25	40
Abdomen	10	40
Pelvis	25	40
Upper arms and elbow joints	30	3
Lower arms and wrist joints	40	2
Hands and fingers	75	0,6
Thighs and knees	50	75
Lower legs	60	75

NOTE Mass values for thighs, knees and lower legs are set to the full body weight, since these body parts are not free to recoil or retract from impact while the operator is standing.

For each body region, the maximum permissible energy transfer can be calculated as a function of the maximum force or maximum pressure values shown in Table A.2 using Formula (A.1):

$$E = \frac{F_{max}^{\ 2}}{2k} = \frac{A^2 p_{max}^{\ 2}}{2k} \qquad \text{(A.1)}$$

where

E is transfer energy;

F_{max} is the maximum contact force for specific body region (see Table A.2);

$p_{\max}$ is the maximum contact pressure for specific body area (see Table A.2);

k is the effective spring constant for specific body region (see Table A.3);

A is the area of contact between robot and body region.

Applying Formula (A.1) to the transient contact values in Table A.2 results in the transfer of energy limit values for each body region as shown in Table A.4.

Table A.4 — Energy limit values based on the body region model

Body region	Maximum transferred energy E J
Skull and forehead	0,23
Face	0,11
Neck	0,84
Back and shoulders	2,5
Chest	1,6
Abdomen	2,4
Pelvis	2,6
Upper arms and elbow joints	1,5
Lower arms and wrist joints	1,3
Hands and fingers	0,49
Thighs and knees	1,9
Lower legs	0,52

A.3.5 Relationship between transferred energy and robot speed during transient contact

Once the energy transfer limit value for the contact scenario is established, it can be used to identify the maximum speed at which the robot would be able to move through the collaborative workspace, while maintaining potential pressure and force values below the threshold limits in Table A.2, if contact between the collaborative robot system and operator were to occur.

The assumption behind the derivation of the speed limit for the contact is to equate the spring energy of the human body region to the total kinetic energy in the centre-of-mass coordinates, assuming fully inelastic contact. The energy in this model is expressed as Formula (A.2):

$$E = \frac{F^2}{2k} = \frac{1}{2}\mu v_{\mathrm{rel}}{}^2 \qquad \text{(A.2)}$$

where

v_{rel} is the relative speed between the robot and the human body region;

μ is the reduced mass of the two-body system, which is expressed by Formula (A.3):

$$\mu = \left(\frac{1}{m_H} + \frac{1}{m_R} \right)^{-1} \qquad \text{(A.3)}$$

where

m_H is the effective mass of the human body region (see Table A.3);

m_R is the effective mass of the robot as a function of robot posture and motion (see Figure A.3), which is expressed by Formula (A.4):

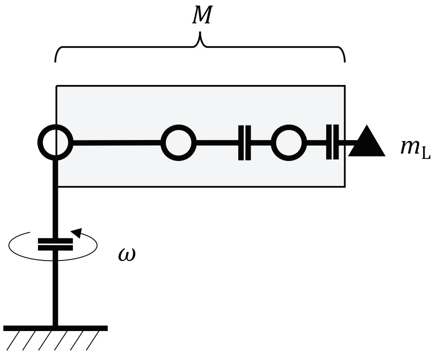
$$m_R = \frac{M}{2} + m_L \qquad \text{(A.4)}$$

where

m_L is the effective payload of the robot system, including tooling and workpiece;

M is the total mass of the moving parts of the robot;

NOTE The values for m_L and M are required in the information for use (see 7.6).



Key

m_L	effective payload of robot system
M	total mass of moving parts of robot
ω	rotational speed

Figure A.3 — Simplified mass distribution model

Thus, solving Formula (A.2) for v_{rel} gives Formula (A.5):

$$v_{rel} = \frac{F}{\sqrt{\mu k}} = \frac{pA}{\sqrt{\mu k}} \qquad \text{(A.5)}$$

where p is the maximum permissible pressure value (see Table A.2).

This can be directly specified to the maximum permissible values in Formula (A.6):

$$v_{rel,max} = \frac{F_{max}}{\sqrt{\mu k}} = \frac{p_{max} A}{\sqrt{\mu k}} \qquad \text{(A.6)}$$

To apply Formula (A.6), first compute the reduced mass of the two body system, μ, based on m_R and m_H, determine p_{max} based on the values provided in Table A.1, then determine k based on the values provided in Table A.3.

Contact area A is defined by the smaller of the surface areas of the robot or the operator. In situations where the body contact surface area is smaller than robot contact surface area, such as the operator's hands or fingers, the body contact surface area shall be used. If contact between multiple body areas with different potential surface contact areas could occur, the value A that yields the lowest $v_{\mathrm{rel,max}}$ shall be used.

Speed limit values, expressed in mm/s, for unconstrained transient contact that can be derived using the body contact model, assuming a contact area A value of 1 cm^2, are shown in Table A.5. Plots of the speed limit values are shown in Figure A.4. A risk assessment utilizing actual values for a given collaborative robot system shall be conducted and the values computed in that risk assessment shall be used to determine whether the collaborative robot cell meets its intended objectives.

Table A.5 — Example of calculated transient contact speed limit values based on the body model

Body region	**Speed limit as a function of robot effective mass, based on maximum pressure value with an area of 1 cm^2** mm/s					
	1	**2**	**5**	**10**	**15**	**20**
Hand/finger	2 400	2 200	2 000	2 000	2 000	1 900
Lower arm	2 200	1 800	1 500	1 400	1 400	1 300
Upper arm	2 400	1 900	1 500	1 400	1 300	1 300
Abdomen	2 900	2 100	1 400	1 000	870	780
Pelvis	2 700	1 900	1 300	930	800	720
Upper leg	2 000	1 400	920	670	560	500
Lower leg	1 700	1 200	800	580	490	440
Shoulders	1 700	1 200	790	590	500	450
Chest	1 500	1 100	700	520	440	400

© ISO 2016 – All rights reserved

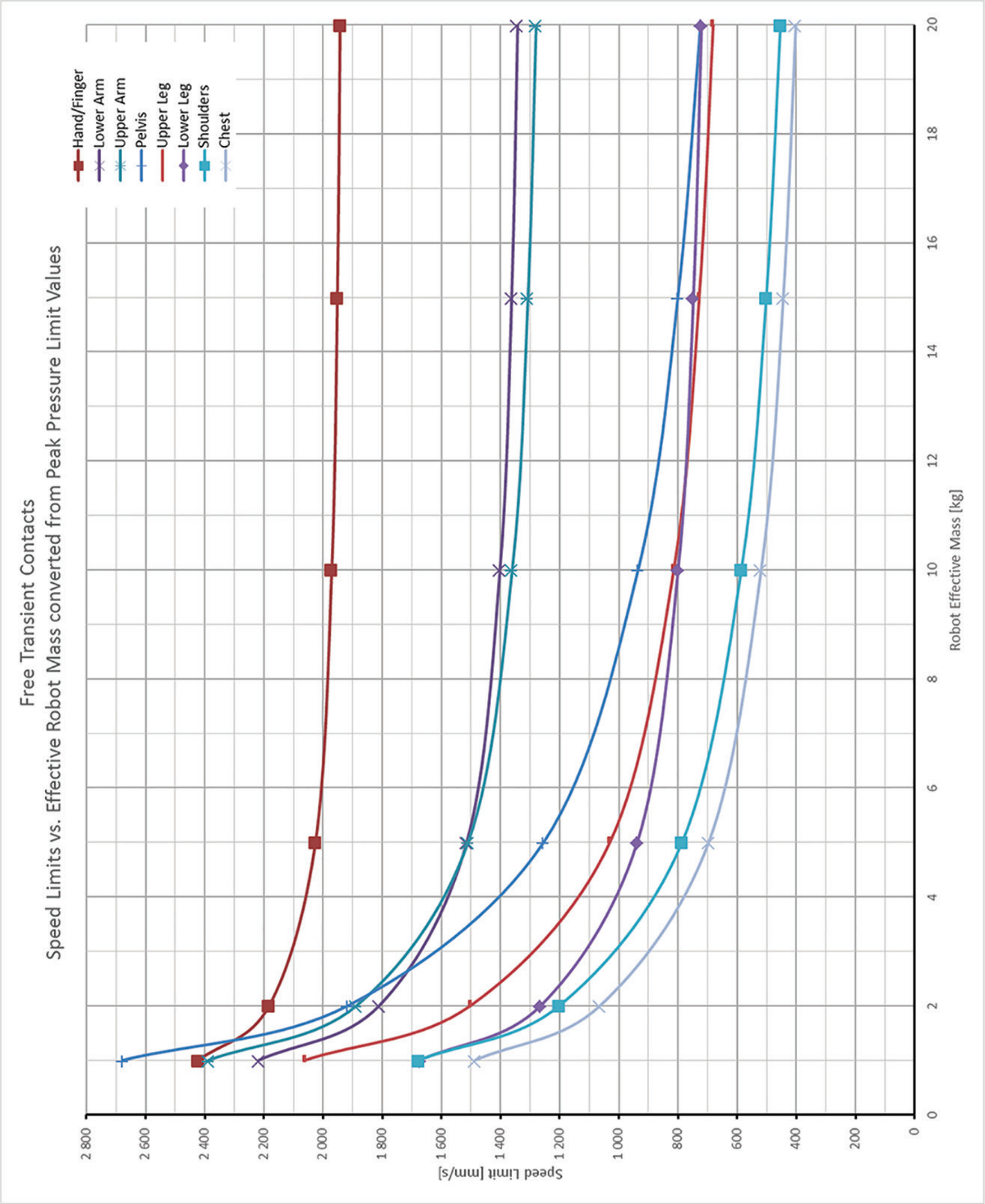


Figure A.4 — Graphical representation of calculated speed limit based on the body model

In some cases during quasi-static contact, there could be an initial peak in force or pressure, consisting of a very short duration, as m_H and m_R reach an equilibrium energy transfer during the clamping period. If such an initial force or pressure peak exists, and can be measured through instrumentation that can distinguish the initial force or pressure from the equilibrium force or pressure, the initial force or pressure value shall be limited by the relevant transient contact value.

A.3.6 Limits to body model

The body model is a means by which integrators of collaborative robot systems can use scientific principles to set appropriate limits associated with risk assessments on power and force limited collaborative robot operations. This is a new field of study and is the subject of ongoing investigation and research.

Furthermore, the body model is presented as a means whereby a robot integrator can apply scientific principles and a standardized approach to considerations pertaining to a risk assessment involving a hypothetical contact situation between an operator and a power and force limiting robot.

The transient contact between a robot and a human body part is assumed to result in a fully inelastic two-body collision. It is likely that the actual transient contact scenario would lie between a perfectly elastic and a perfectly inelastic collision.

The two-body contact model used for the transient contact analysis assumes that the contact surface area between a robot and a human body part is flat, with a uniform pressure distribution across the surface area. There is ongoing research evaluating the effects of different geometric shapes and contact configurations associated with the body model. The actual contact conditions, including the geometric shape of the contact area, would need to be compared against the force and pressure values in Table A.2 though measurement or calculations.

© ISO 2016 – All rights reserved

Bibliography

[1] IEC/TS 62046:2008, *Safety of machinery — Application of protective equipment to detect the presence of persons*

[2] EN 12453:2000, *Industrial, commercial and garage doors and gates — Safety in use of power operated doors — Requirements*

[3] MEWES D., & MAUSER F. Safeguarding Crushing Points by Limitation of Forces. Int. J. Occup. Saf. Ergon. 2003, **9** (2) pp. 177–191

[4] SUITA K., YAMADA Y., TSUCHIDA N., IMAI K., IKEDA H., SUGIMOTO N. A Failure-to-safety "Kyozon" system with simple contact detection and stop capabilities for safe human-autonomous robot coexistence. IEEE International Conference on Robotics and Automation 0-7803-1965-6/95. 1995

[5] Research project No. FP-0317: Collaborative robots – Investigation of pain sensibility at the Man-Machine-Interface. Institute for Occupational, Social and Environmental Medicine at the Johannes Gutenberg University of Mainz, Germany. Final report December 2014

[6] BG/BGIA Risk assessment recommendations according to machinery directive. Design of workplaces with collaborative robots. U 001/ 2009e October 2009 edition, revised February 2011 http://publikationen.dguv.de/dguv/pdf/10002/bg_bgia_empf_u_001e.pdf

[7] YAMADA Suita, IKEDA Sugimoto, MIURA Nakamura Pain: Evaluation of pain tolerance based on a biomechanical method for human- robot- coexistence. Transactions of the Japan Society of Mechanical Engineers. No 96-0689. 1997-8

[8] REPORT NO 88-5 USAARL Anthropometry and Mass Distribution for Human Analogues. Military Male Aviators, Vol. I, 1988.

[9] BEHRENS Roland, & ELKMANN Norbert Experimentelle Verifikation der biomechanischen Belastungsgrenzen bei Mensch-Roboter-Kollisionen: Phase I, Fraunhofer-Institut fuer Fabrikbetrieb und -automatisierung IFF, Magdeburg, October 2014

© ISO 2016 – All rights reserved

ICS 25.040.30

Price based on 33 pages

© ISO 2016 – All rights reserved

This page deliberately left blank

NO COPYING WITHOUT BSI PERMISSION EXCEPT AS PERMITTED BY COPYRIGHT LAW

British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards -based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email bsmusales@bsigroup.com.

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK

Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

Copyright

All the data, software and documentation set out in all British Standards and other BSI publications are the property of and copyrighted by BSI, or some person or entity that owns copyright in the information used (such as the international standardization bodies) and has formally licensed such information to BSI for commercial publication and use. Except as permitted under the Copyright, Designs and Patents Act 1988 no extract may be reproduced, stored in a retrieval system or transmitted in any form or by any means – electronic, photocopying, recording or otherwise – without prior written permission from BSI. Details and advice can be obtained from the Copyright & Licensing Department.

Useful Contacts:

Customer Services
Tel: +44 845 086 9001
Email (orders): orders@bsigroup.com
Email (enquiries): cservices@bsigroup.com

Subscriptions
Tel: +44 845 086 9001
Email: subscriptions@bsigroup.com

Knowledge Centre
Tel: +44 20 8996 7004
Email: knowledgecentre@bsigroup.com

Copyright & Licensing
Tel: +44 20 8996 7070
Email: copyright@bsigroup.com