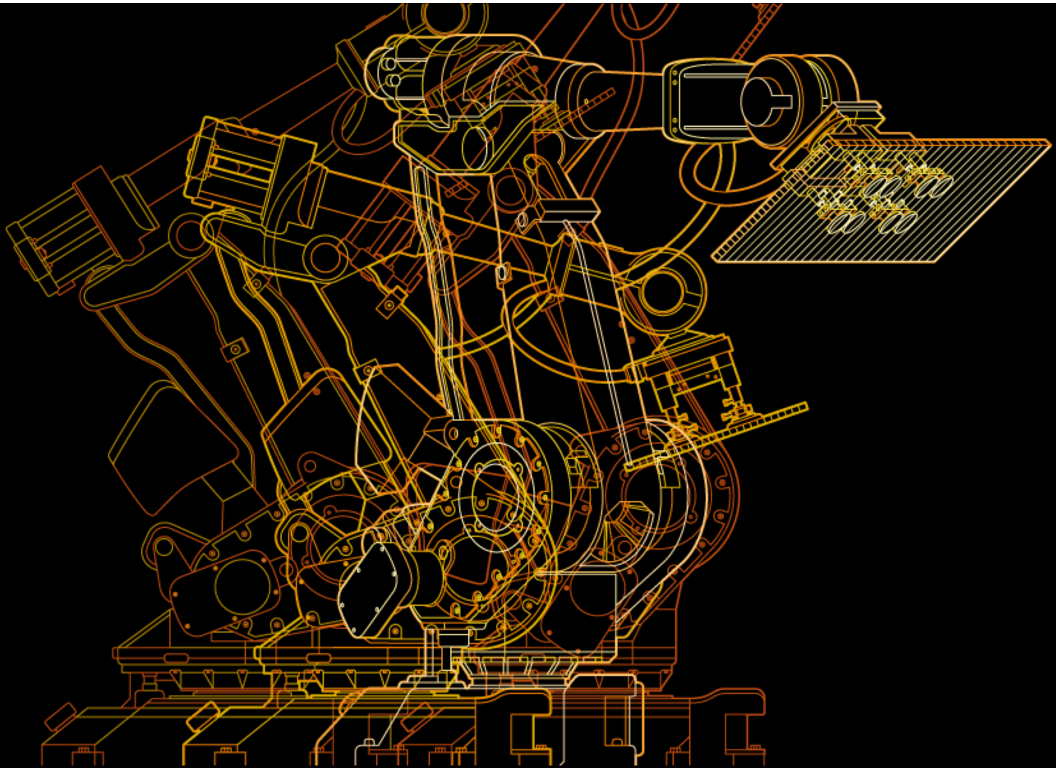

Björn Matthias – ABB Corporate Research – 2015-03-11

ISO/TS 15066 - Collaborative Robots
Present Status

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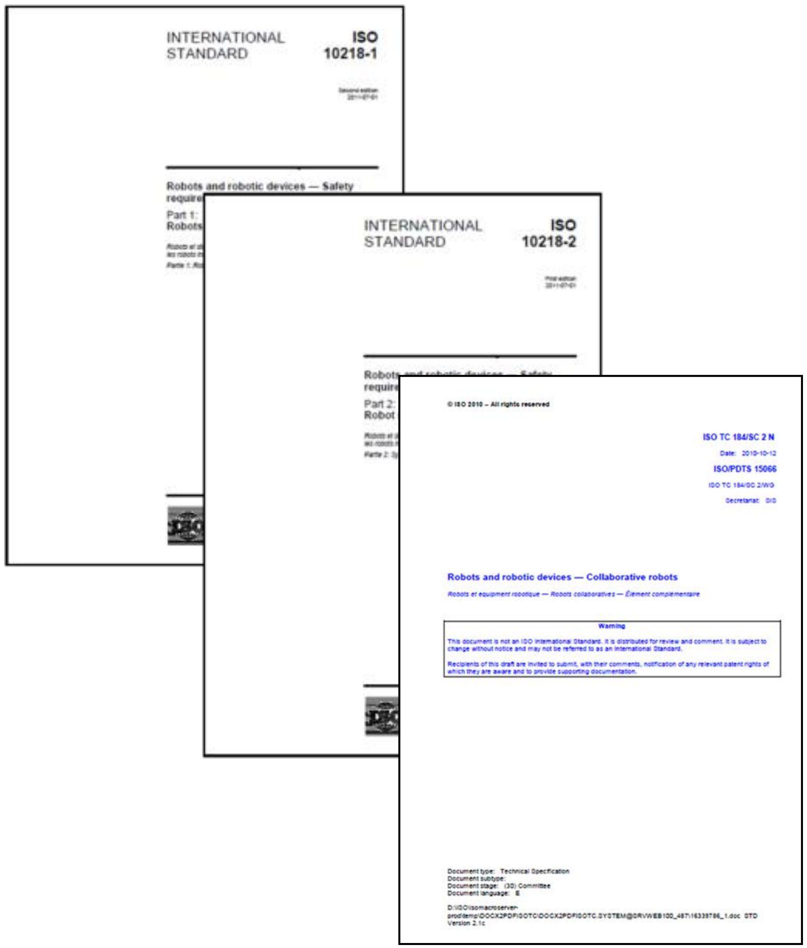
ISO/TS 15066 – Present Status
Overview



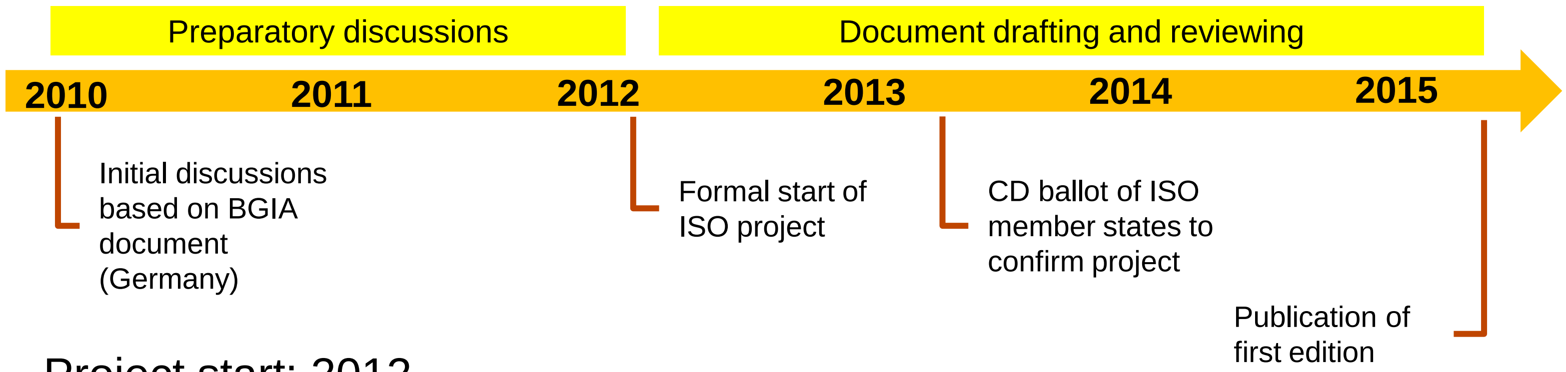
- ISO project overview
- ISO project timeline
- Collaborative operation
- Collaborative work space
- Types of collaborative operation
  - Safety-rated monitored stop
  - Hand guiding
  - Speed and separation monitoring
    - Minimum separation distance
  - Power and force limiting
    - Biomechanical limits

ISO/TS 15066 – Present Status
ISO Project Overview

- Motivation and Purpose
  - End users waiting for standards document before willing to implement applications
  - Complex nature of protection schemes that are less established than conventional guarding and ESPE’s (electro-sensitive protective equipment, e.g. light curtains, laser scanners)
  - Meet the developing interest in collaborative robots with specific guidance
- Objective
  - Generate a TS (technical specification) document, valid for 3 years
  - After 3 years, review options
    - Confirm for 3 more years (if still deemed unsuitable for a standard)
    - Integrated into ISO 10218-2 (this is the preferred outcome)
    - Discard (if it turns out to be without practical relevance)
- Responsible international working group
  - ISO / TC184 (Automation systems) / SC2 (Robots and robotic devices) / WG3 (Industrial safety)
  - Convenor: Pat Davison, Robotic Industries Association (USA)
- Remaining work before first publication
  - Review and process remaining technical and editorial comments from WG3 members

ISO/TS 15066 – Present Status
ISO Project Timeline

Concurrent research work on biomechanical criteria at:
- DGUV/IFA (formerly BGIA)
- University of Mainz, Occupational Medicine
- Fraunhofer IFF, Magdeburg



- Project start: 2012
- Project end: 2015-12-05
- Future meeting schedule
  - SC 2/WG 3 40th Meeting: 2015 June 15-17, at Daimler, Sindelfingen, Germany
  - TC 184/SC 2 22nd Plenary Meeting: 2015 June 18-19, at BGHM, Stuttgart, Germany
  - SC 2/WG 3 41st Meeting: 2015 December 7-9, in Yokohama, Japan
- First publication of ISO/TS 15066: 2015-12-05

ISO/TS 15066 – Present Status
Collaborative Operation – Definition

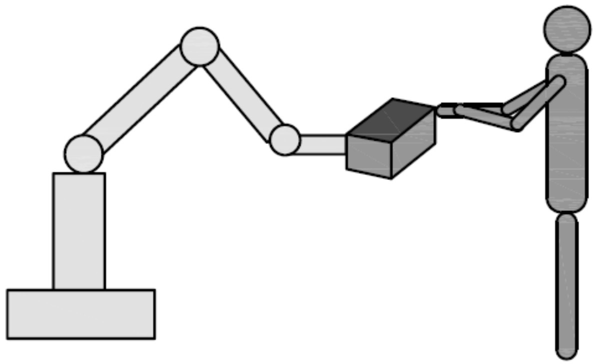
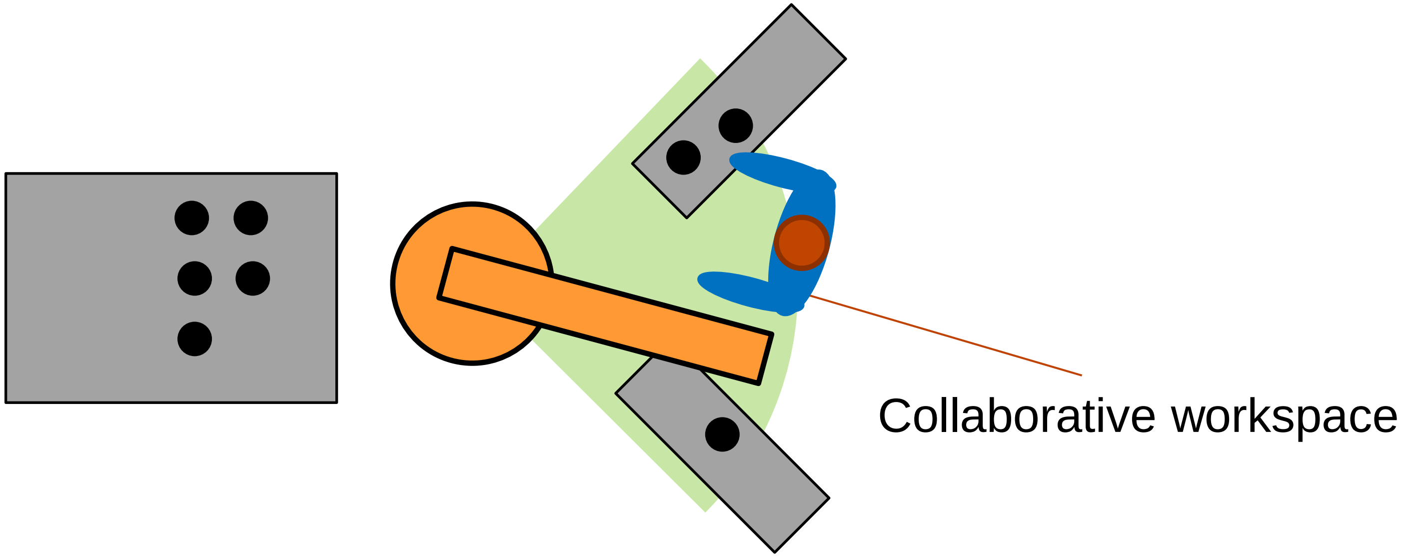


Figure 2 — Suggested labelling design (ISO 10218-2:2011, Fig. 2)

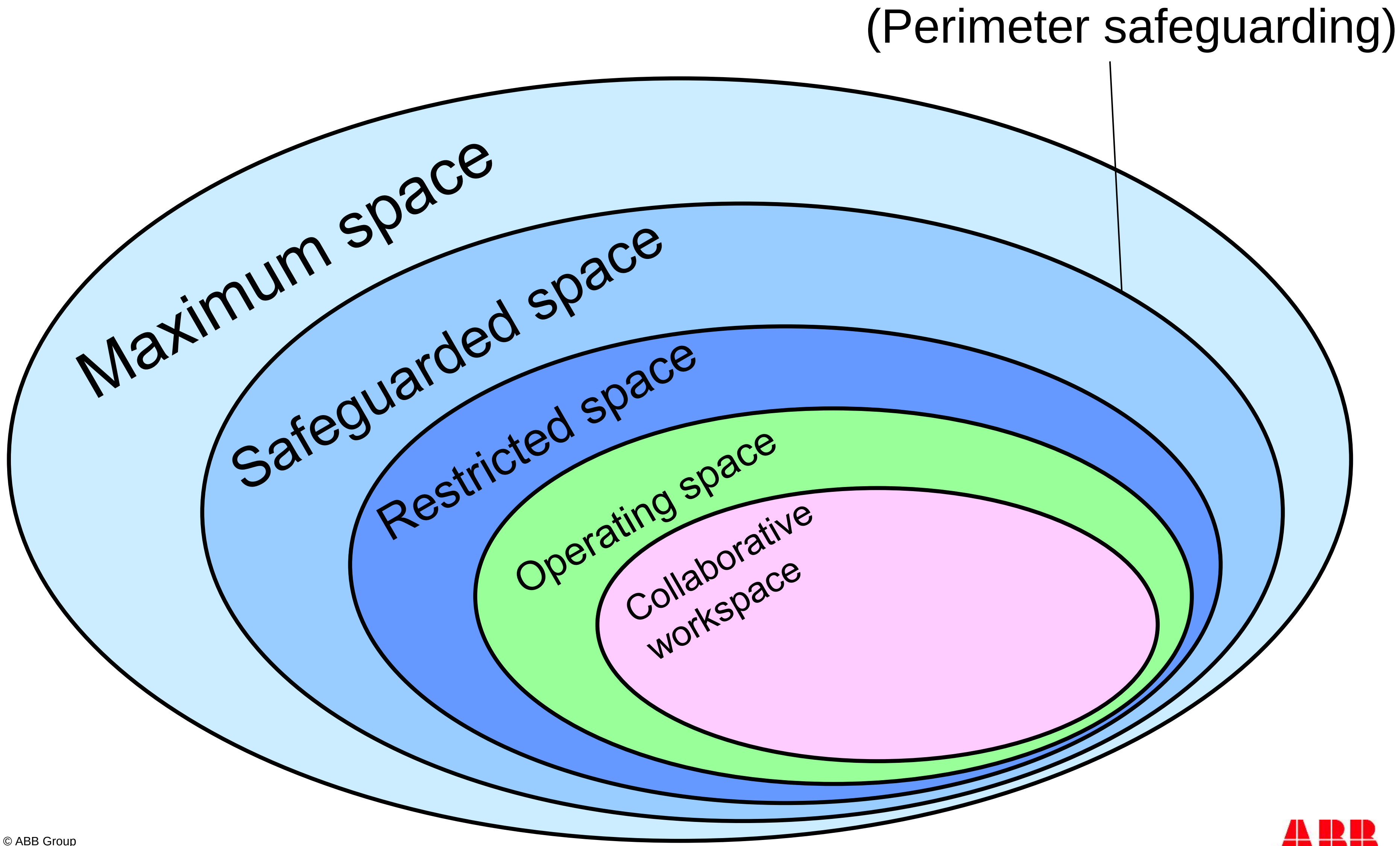
- **ISO 10218-1:2011, clause 3.4**
- **collaborative operation**
- state in which purposely designed robots work in direct cooperation with a human within a defined workspace

ISO/TS 15066 – Present Status
Collaborative Work Space – Definition

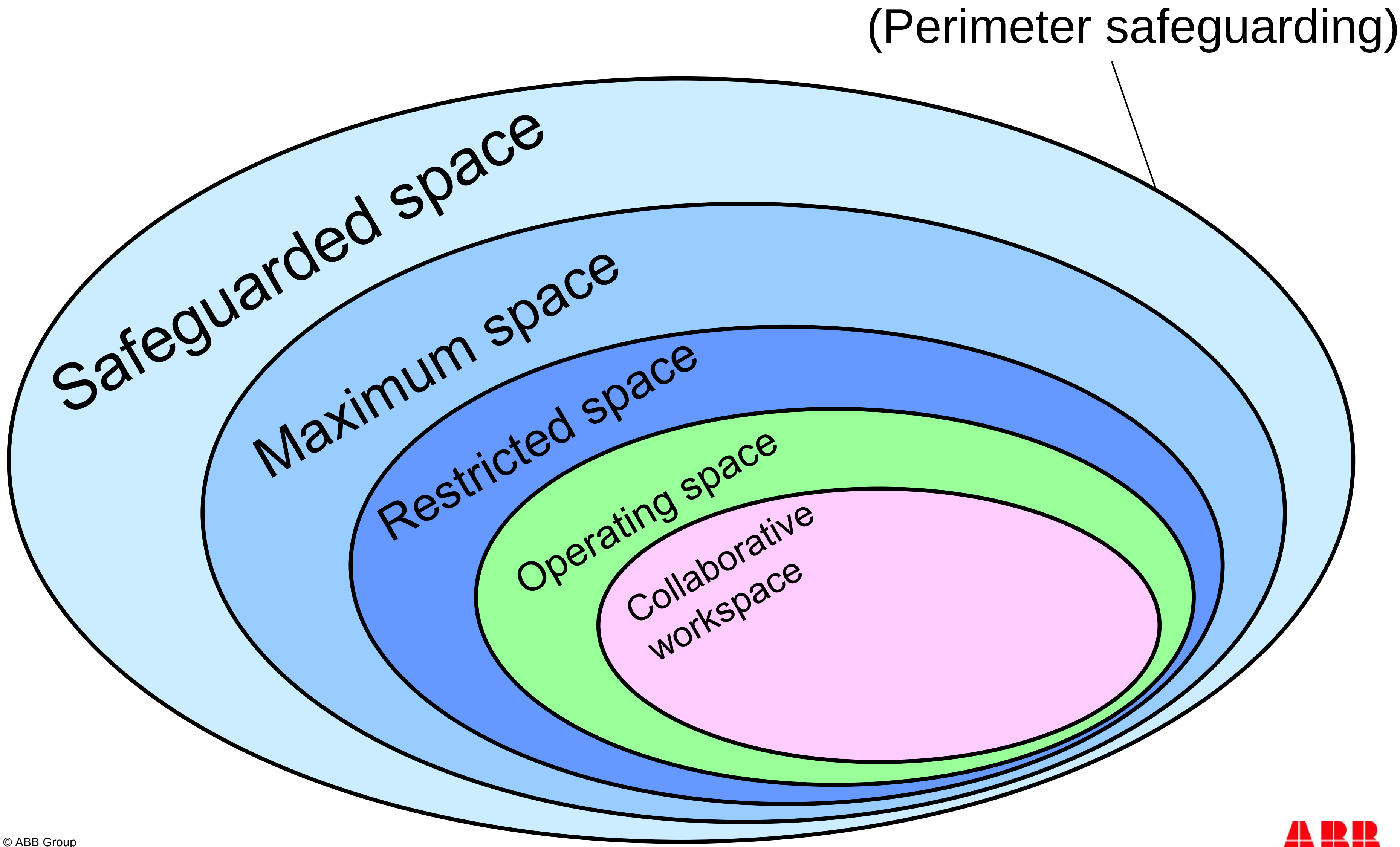


- **ISO 10218-1:2011, clause 3.5**
- **collaborative workspace**
- workspace within the safeguarded space where the robot and a human can perform tasks simultaneously during production operation

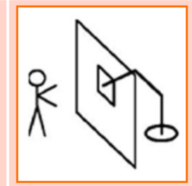
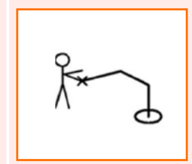
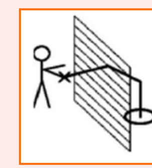
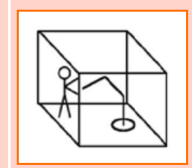
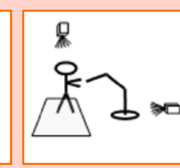
Hierarchy of Spaces
ISO 10218-1:2011 and ISO 10218-2:2011



Hierarchy of Spaces
ISO 10218-1:2011 and ISO 10218-2:2011



Types of Collaborative Operation According to ISO 10218, ISO/TS 15066

ISO 10218-1, clause	Type of collaborative operation	Main means of risk reduction	Pictogram (ISO 10218-2)
5.10.2	Safety-rated monitored stop (Example: manual loading-station)	No robot motion when operator is in collaborative work space	
5.10.3	Hand guiding (Example: operation as assist device)	Robot motion only through direct input of operator	 
5.10.4	Speed and separation monitoring (Example: replenishing parts containers)	Robot motion only when separation distance above minimum separation distance	 
5.10.5	Power and force limiting by inherent design or control (Example: *ABB Dual-Arm Concept Robot* collaborative assembly robot)	In contact events, robot can only impart limited static and dynamics forces	

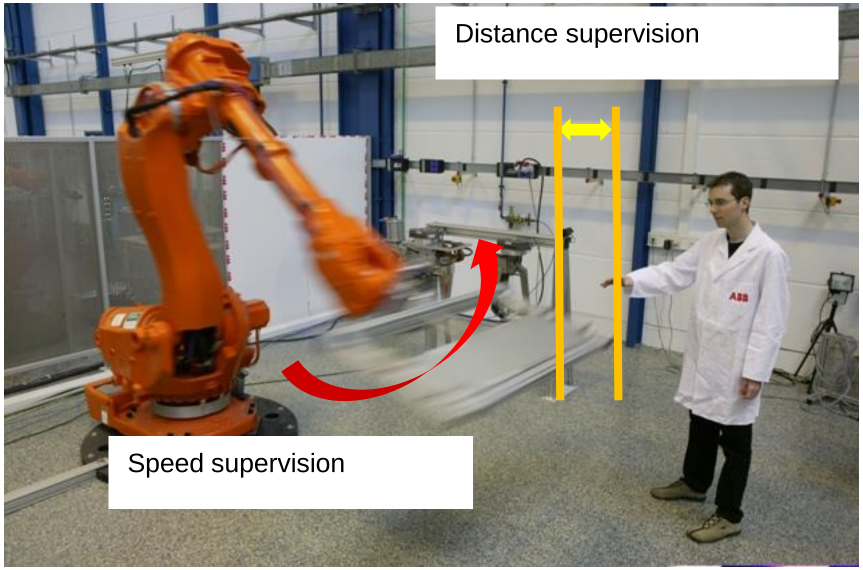
ISO/TS 15066 – Present Status
Safety-Rated Monitored Stop

- Clauses in standards and TS
  - ISO 10218-1, clause 5.10.2
  - ISO 10218-2, clause 5.11.5.2
  - ISO/TS 15066, clause 5.5.1
- Risk reduction
  - Ensure robot standstill whenever a worker is in collaborative workspace
- Achieved by
  - Supervised standstill - Category 2 stop (IEC 60204-1)
  - Category 0 stop in case of fault (IEC 60204-1)
- Typical applications
  - Loading / unloading end-effector
  - Ergonomic adaptation

ISO/TS 15066 – Present Status
Hand Guiding

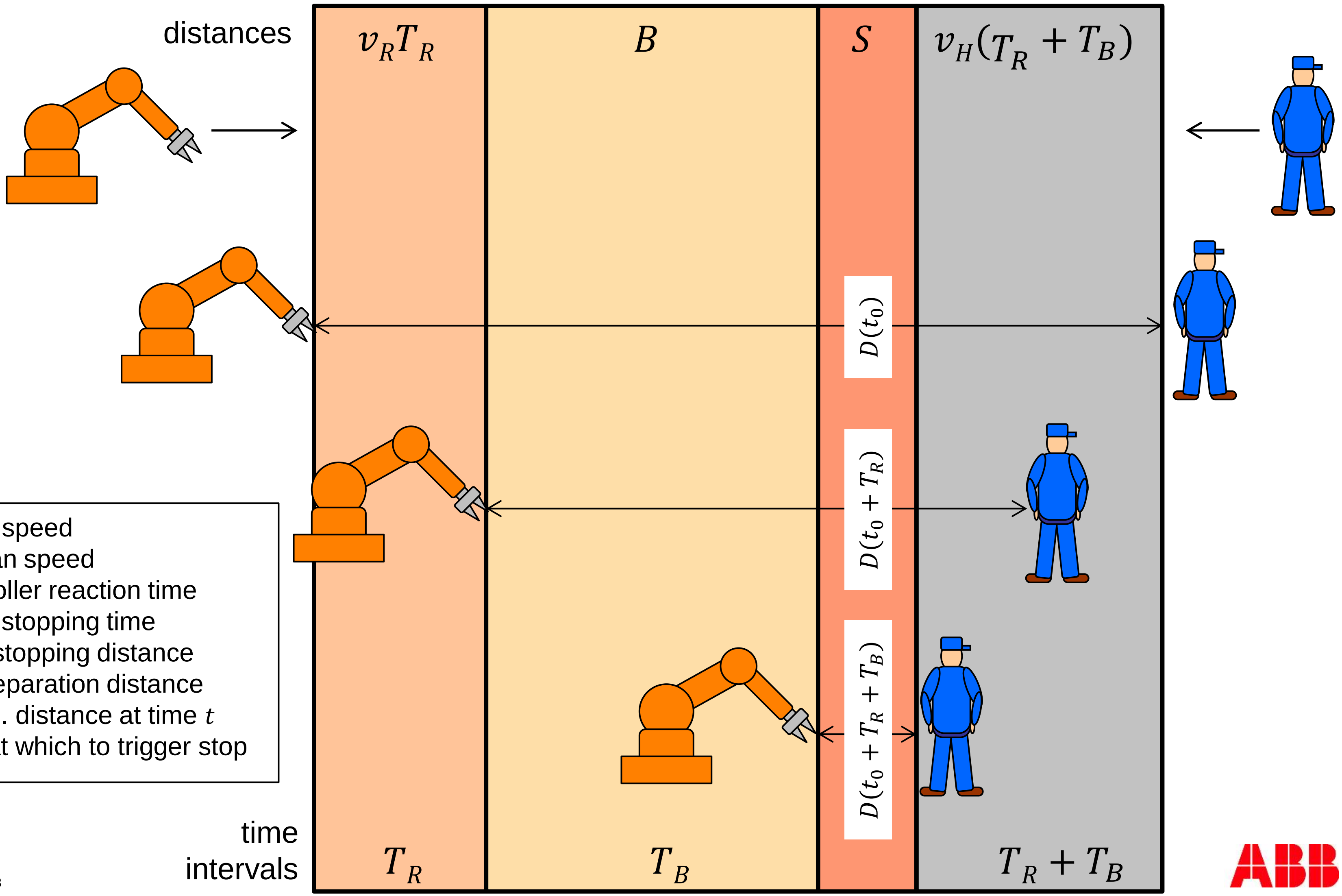
- Clauses in standards and TS
  - ISO 10218-1, clause 5.10.3
  - ISO 10218-2, clause 5.11.5.3
  - ISO/TS 15066, clause 5.5.2
- Risk reduction
  - Provide worker with direct control over robot motion at all times in collaborative workspace
- Achieved by
  - Controls close to end-effector
  - Input means for motion commands
  - Emergency stop
  - Enabling device
- Typical applications
  - Lift assist
  - Ergonomic adaptation
  - Load positioning

ISO/TS 15066 – Present Status
Speed and Separation Monitoring



- Clauses in standards and TS
  - ISO 10218-1, clause 5.10.4
  - ISO 10218-2, clause 5.11.5.4
  - ISO/TS 15066, clause 5.5.3
- Risk reduction
  - Maintain sufficient distance between worker and robot in collaborative workspace
- Achieved by
  - Supervision of distance, speed
  - Protective stop if minimum separation distance or speed limit is violated
  - Consider braking distance in minimum separation distance
- Applications
  - Working in common area on separate tasks
- Additional requirements on safety-rated periphery
  - Safety-rated position information

ISO/TS 15066 – Present Status
Minimum Separation Distance



v_R = robot speed
v_H = human speed
T_R = controller reaction time
T_B = robot stopping time
B = robot stopping distance
S = min. separation distance
$D(t)$ = sep. distance at time t
t_0 = time at which to trigger stop

ISO/TS 15066 – Present Status
Power and Force Limiting



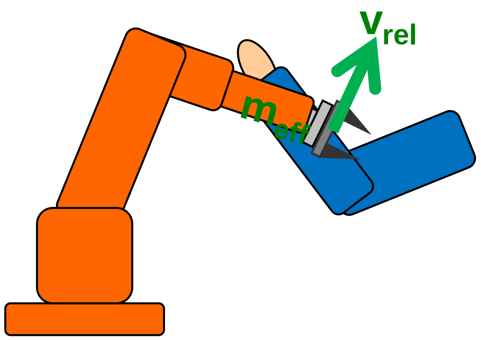




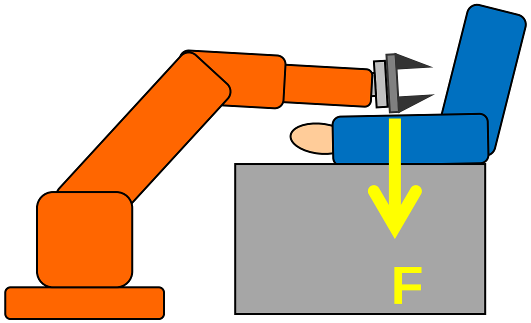



- Clauses in standards and TS
  - ISO 10218-1, clause 5.10.5
  - ISO 10218-2, clause 5.11.5.5
  - ISO/TS 15066, clause 5.5.4
- Incidental physical contact possible
  - Transient
  - Quasi-static
- Risk reduction
  - Limiting mechanical loading of human-body parts by moving parts of robot, end-effector or work piece
- Typical measures
  - Low inertia, suitable geometry and material, sensory input, control functions to limit speeds, torques, …
- Applications in mixed environment, involving possibility of transient and/or quasi-static physical contact

ISO/TS 15066 – Present Status
Limit Criteria on Mechanical Loading



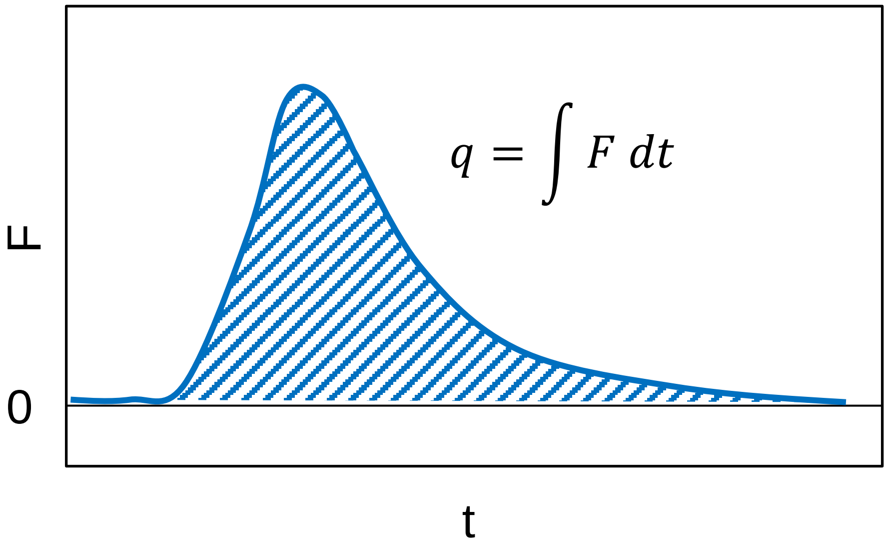
Free impact (transient)

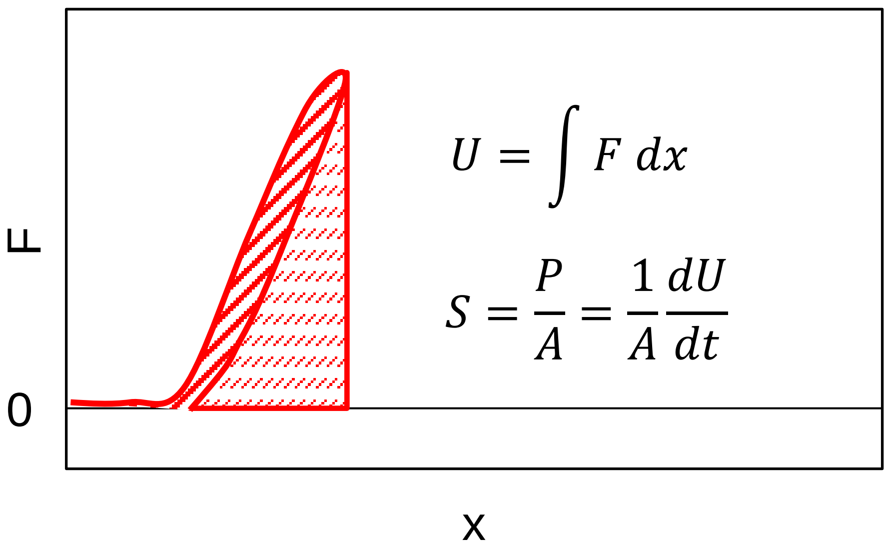


Constrained impact (transient or quasi-static)

- Transient contact
  - Short (approx. max. 50 ms), robot control cannot react
  - Hazard is from energy transfer through contact area in certain time (power flux density)
  - Energy transfer depends on relative speed, effective masses of moving robot and body region, contact area
  - Protective measures
    - Robot design, shape, mass, …
    - Robot control functions, speed, …
    - Appropriate application environment
- Quasi-static contact
  - Extended (longer than transient), robot control can reduce speed and force
  - Hazard is from application of pressure and force
  - Force depends on kinematic superposition of joint torques, pressure also on contact area
  - Protective measures
    - Robot design, shape, mass, …
    - Robot control functions, torques, …
    - Appropriate application environment

Transient limit criteria related to robot design + control



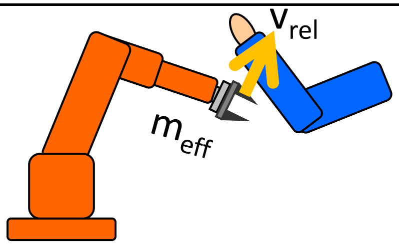


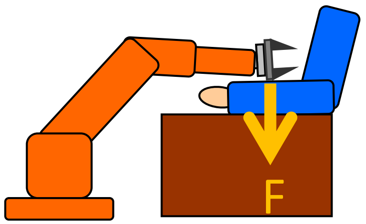
- Force F $[N]$
- Pressure p $[\frac{N}{m^2} = \frac{J}{m^3}]$
- Momentum transfer q $[\frac{kg \cdot m}{s}]$
- Energy transfer U $[J]$
- Power P $[W = \frac{J}{s}]$
- Energy flux density K $[\frac{J}{m^2}]$
- Power flux density S $[\frac{W}{m^2}]$
- Contact area A $[m^2]$

Biomechanical Limit Criteria

ISO / TS 15066 – clause 5.5.4 “Power and force limiting”

	Transient Contact	**Quasi-Static Contact**
Description	• Contact event is “short” (< 50 ms) • Human body part can usually recoil	• Contact duration is “extended” • Human body part cannot recoil, is trapped
Limit Criteria	• Peak forces, pressures, stresses • Energy transfer, power density	• Peak forces, pressures, stresses
Accessible in Design or Control	• Effective mass (robot pose, payload) • Speed (relative) • Contact area, duration	• Force (joint torques, pose) • Contact area, duration





Risk Reduction Measures

	Transient Contact	Quasi-Static Contact
Mechanical Design	• Reduce effective mass • Increase contact area • Increase contact duration	• Increase contact area
Control Design	• Reduce relative speed • (Reduce effective mass by suitable choices of pose)	• Decrease maximum joint torques, forces • Decrease contact duration

- Design choices are a balance between performance characteristics and safety requirements
- Safety-related control functions must be designed and implemented according to appropriate choice of safety performance level (PL) / safety integrity level (SIL) and designated architecture (ISO 13849-1, IEC 62061)

ISO/TS 15066 – Present Status
Literature on Biomechanical Loading Limits

- Pressure and force peak values
  - Pain tolerance values (Yamada et al.)
  - Values from BGIA literature study (Ottersbach et al.)
  - Pain thresholds, quasi-static, Univ. Mainz (Muttray et al.)
  - EN 415-8:2011, Safety of packaging machines – Part 8: Strapping machines
  - EN 12453, Industrial, commercial and garage doors and gates - Safety in use of power operated doors
- Energy flux density
  - Approx. 0.1 J/cm^2 energy input density → pain threshold (Povse, Munich et al.)
  - Approx. 1 J/cm^2 energy input density → contusion threshold (Brinkmann + Madea; Townsend; Haddadin et al.)
  - Pain and contusion thresholds, transient, Fraunhofer IFF (Elkmann, Behrens), in preparation

ISO/TS 15066 – Present Status
Biomechanical Loading Limits

- General
  - Body model with measurement points, local spring constant, effective masses
- Pressure and force peak values
  - From results of research at University of Mainz, Prof. Axel Muttray, Institute of Occupational Medicine
  - Data from 75th percentile pain sensation (75% of all subjects experienced the loading value as painful)
  - Tables will quote limit values for
    - Pressures for pain sensation thresholds [N/cm^2]
    - Forces for pain sensation [N]
- Energy flux density
  - Based on results of research at University of Mainz, Prof. Axel Muttray (quasi-static values above) and University of Nagoya, Prof. Yoji Yamada (pain thresholds as function of loading duration)
  - Assumption of model description as fully inelastic 2-body collision, all kinetic energy is deposited in tissue
  - Tables will quote
    - Energies for pain sensation [J]
    - Limits on relative speed [mm/s]

ISO/TS 15066 – Present Status
Body Model

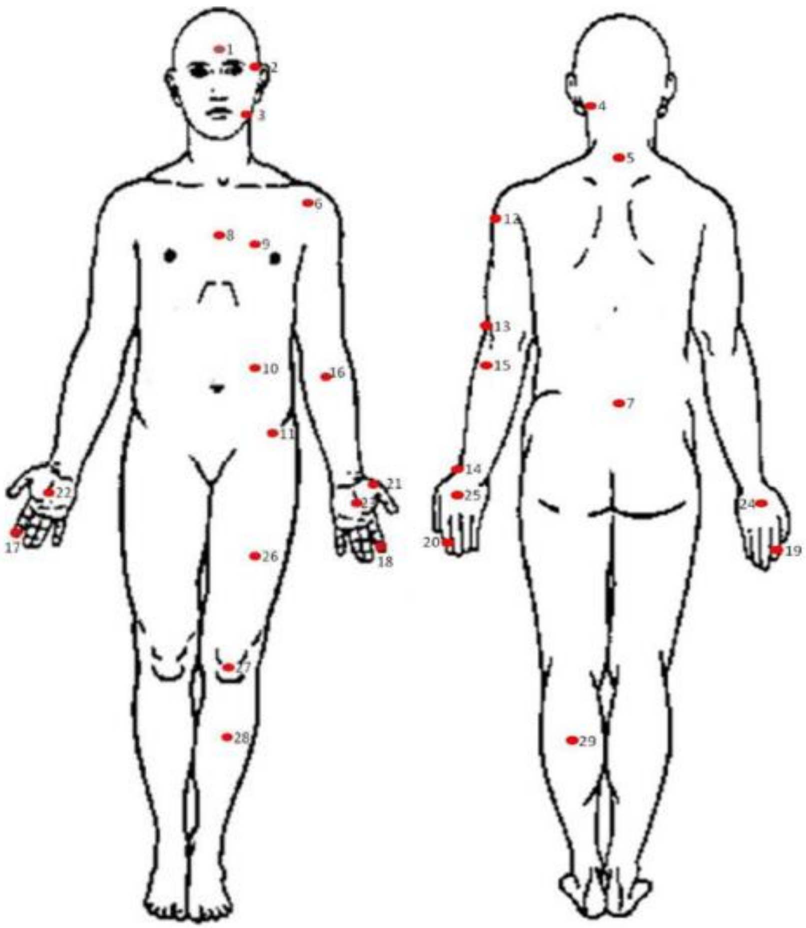


Figure A.1 — Body Model

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
	16	Arm nerve	Front
Lower arms and wrist joints	14	Radial bone	Rear
	15	Forearm muscle	Rear
Hands and fingers	17	Forefinger pad D	Front
	18	Forefinger pad ND	Front
	19	Forefinger end joint D	Rear
	20	Forefinger end joint ND	Rear
	21	Thenar eminence	Front
	22	Palm D	Front
	23	Palm ND	Front
	24	Back of the hand D	Rear
	25	Back of the hand ND	Rear
Thighs and knees	26	Thigh muscle	Front
	27	Kneecap	Front
Lower legs	28	Middle of shin	Front
	29	Calf muscle	Rear

NOTE: D = dominant body side (right or left); ND = non-dominant body side

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