FROM HEAD TO TOE - BIOMECHANICAL THRESHOLDS TO PROTECT ROBOT OPERATORS AGAINST INJURIES

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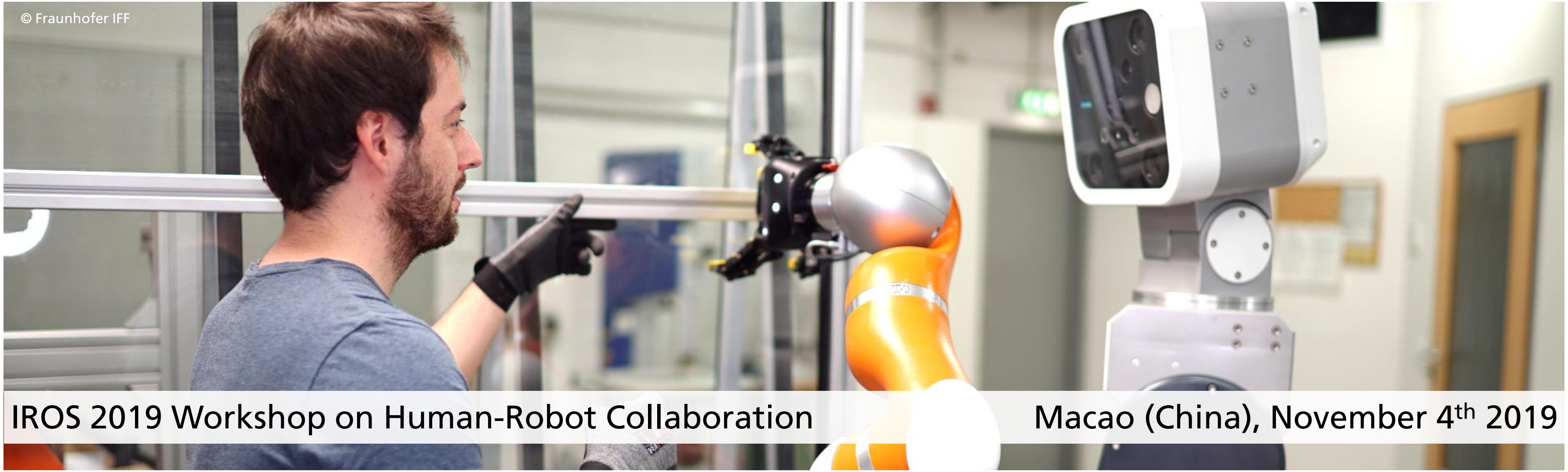

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Introduction

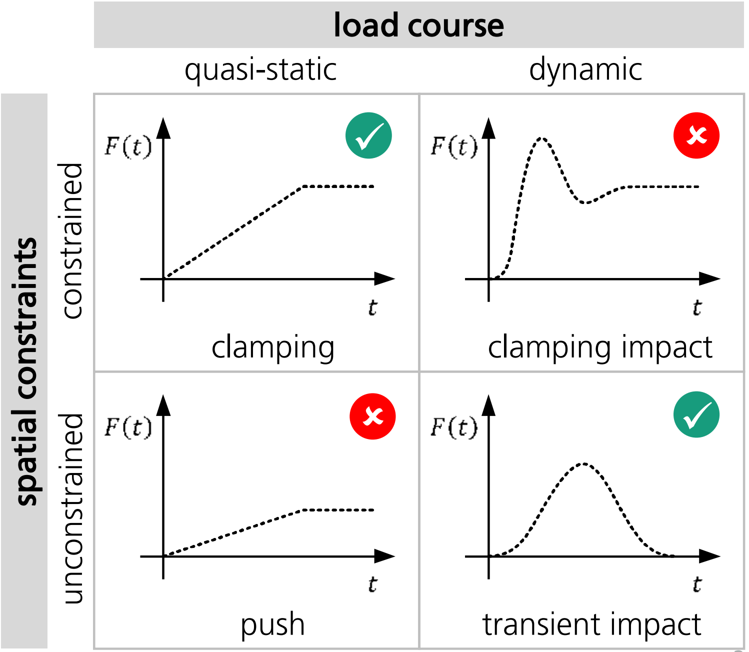
Types of human-robot contacts and their most relevant features

Most relevant features (Haddadin et al. 2009c)

- Load course (force over time): quasi-static or transient
- Spatial constraints: constrained or unconstrained
- Shape of contact area: blunt (incl. semi-sharp) or sharp

Requirements according to ISO/TS 15066 (for PFL)

- No sharp contacts
- Unconstrained contact at low robot velocities (push) are considered as corresponding with a low risk
- Constrained contact at high robot velocities (clamping impact) are not allowed (due to a high injury risk)
- Two types of contact areas:
  - Blunt (force-based limits)
  - Semi-sharp (pressure-based limits)



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State of the art (until 2013)

Data from literature to derive biomechanical thresholds for impacts (transient contact)

Biomechanical trauma studies

Load: external forces acting on the human body

Stress: response of the human body to external load

- Research of more than 800 sources
- Examination with various…
  - Test objects
  - Methodologies
- Considered quantities:
  - Energy and energy density
  - force (frequently used)
  - Pressure / normal stress

Data from literature

We only considered sources about …

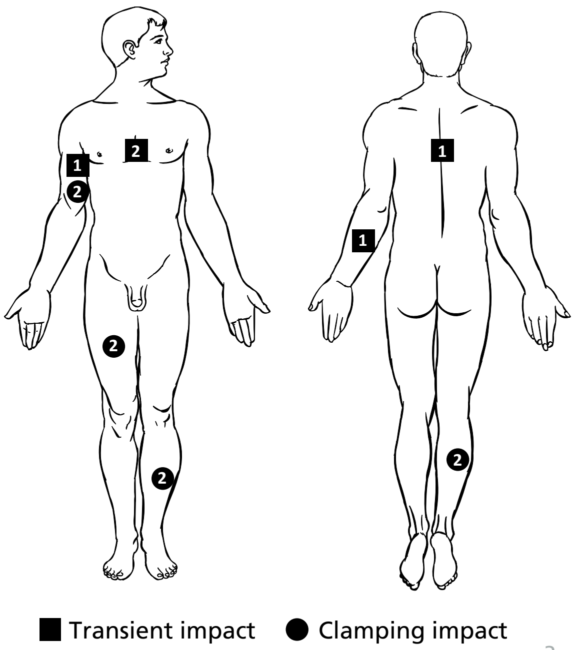
- Studies on slight forms of stress (max. bruise)
- Studies with human volunteers
- Studies with ethical approval

Results:

- Only a few studies on impacts
- No clear specification of the referenced stress limit
- Most frequent focus: the body's response on impacts

Result Goal cannot be achieved with available literature data

Number of impact studies that met the criteria



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State of the art

Current situation in ISO/TS 15066

- Quasi-static pressure values (clamping contact at low robot speeds) *(verified)*
- Quasi-static force values (clamping at low robot velocities) *(non-verified)*
- Scaling factor for transforming pressure values from quasi-static to transient contact (impact) *(non-verified)*
- Scaling factor for transforming force values from quasi-static to transient contact (impact) *(non-verified)*

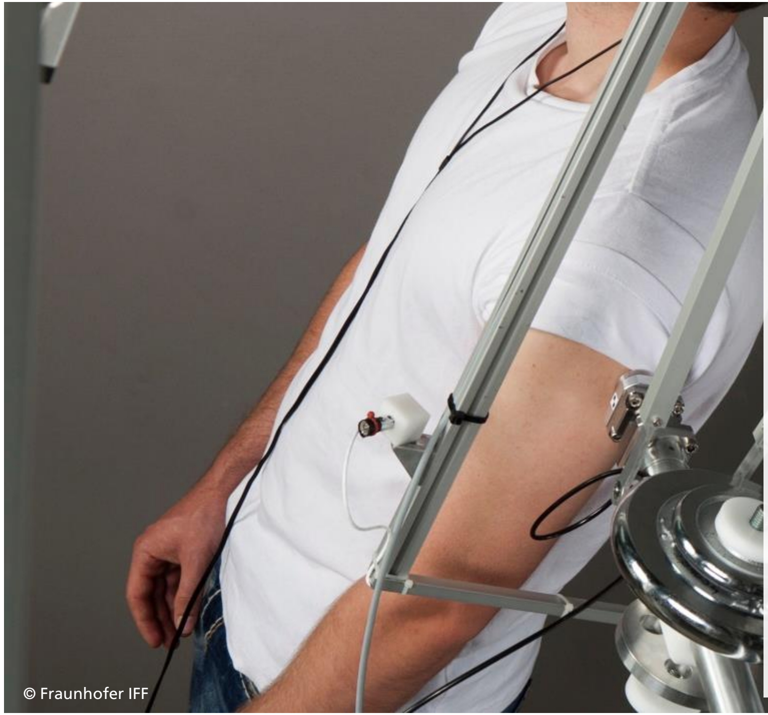
Body region		Specific body area	Quasi-static contact		Transient contact	
			Maximum permissible pressure [a] p_S N/cm²	Maximum permissible force [b] N	Maximum permissible pressure multiplier [c] P_T	Maximum permissible force multiplier [c] F_T
Skull and forehead [d]	1	*Middle of forehead*	*130*	*130*	*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		[illegible]	
Back and shoulders	6	Shoulder joint	[illegible]	[illegible]	[illegible]	2
	7	Fifth lumbar vertebra	[illegible]	[illegible]	[illegible]	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	12	Deltoid muscle	190	150	2	2

Impacts to the head-neck region are currently not allowed

- Table differs human body into 29 body parts
- Maximum stress / consequences: onset of pain
- Intended application:
  - Absolute values for quasi-static contact
  - Scaling factors to transform absolute values (for quasi-static contact) to transient contact (from clamping to impact)
  - Force values for blunt contacts
  - Pressure values for semi-sharp contacts
- ✓ Verified values from volunteer studies
- ↖ Non-verified values from literature

Methodology

Overview on the volunteer studies at Fraunhofer IFF for determining pain and injury thresholds



Limit values for …

- Onset of pain
- Onset of injury (pilot study)

Methodology

- Stress studies with volunteers (impact and clamping)
- Experimental setup:
  - Impact: Pendulum
  - Clamping: Algometer (same which was used by the University of Mainz for their study)
- Gradual increase of impact or clamping load
- Criteria for stopping load test:
  - Onset of pain (transition from a pressure sense to pain)
  - Onset of injury: hematoma or swelling

Methodology
Scientific consortium and partners

Fraunhofer IFF
- Scientific lead
- Acquisition of volunteers
- Load tests
- Result analysis

Supporters
- Injury onset study (initiated by IFF, supported by KUKA and Daimler)
- Pain onset study (contracted by BGHM and DGUV)

Medical Center of the University of Magdeburg
- Ethical approval
- Involved institutions
  - Trauma surgery
  - Forensic medicine
- Risk analysis (health threatening hazards arising from the stress tests)
- Health check of participating volunteers
- Medical support

Initiated and supported by:

BGHM Berufsgenossenschaft Holz und Metall

DGUV Deutsche Gesetzliche Unfallversicherung Spitzenverband

KUKA

DAIMLER

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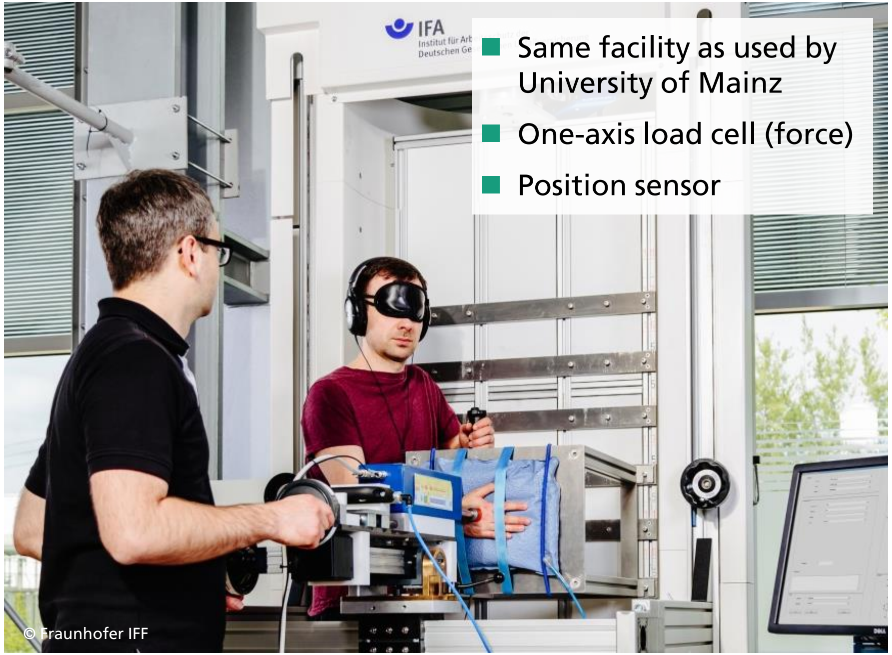
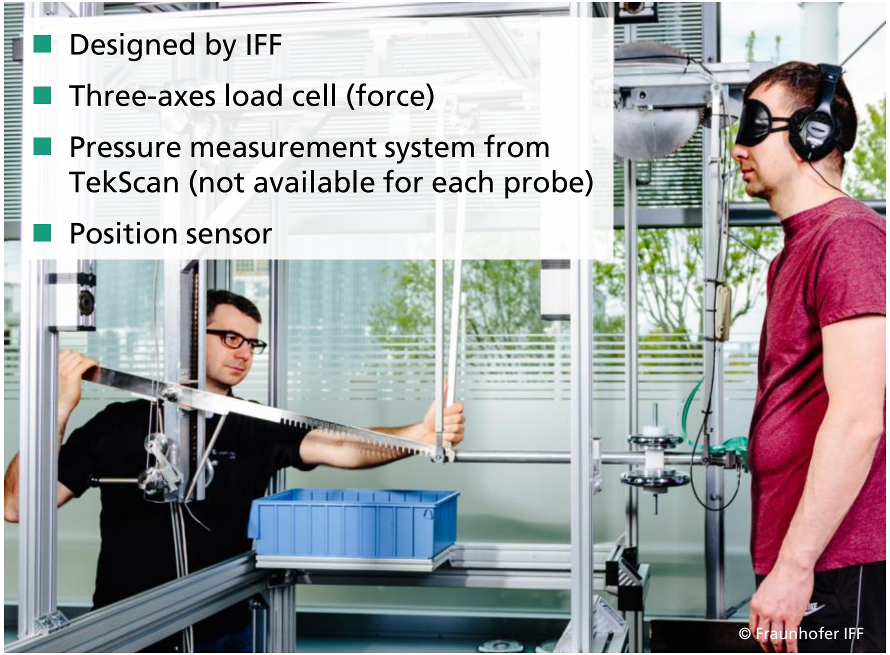
Methodology
Test facilities

Quasi-static loads (clamping)



- Same facility as used by University of Mainz
- One-axis load cell (force)
- Position sensor

Dynamic loads (impact)



- Designed by IFF
- Three-axes load cell (force)
- Pressure measurement system from TekScan (not available for each probe)
- Position sensor

Methodology

Procedure for quasi-static tests

Principle: clamping force is created by a linear guide that pushes a rod against the body part

Features of the algometer

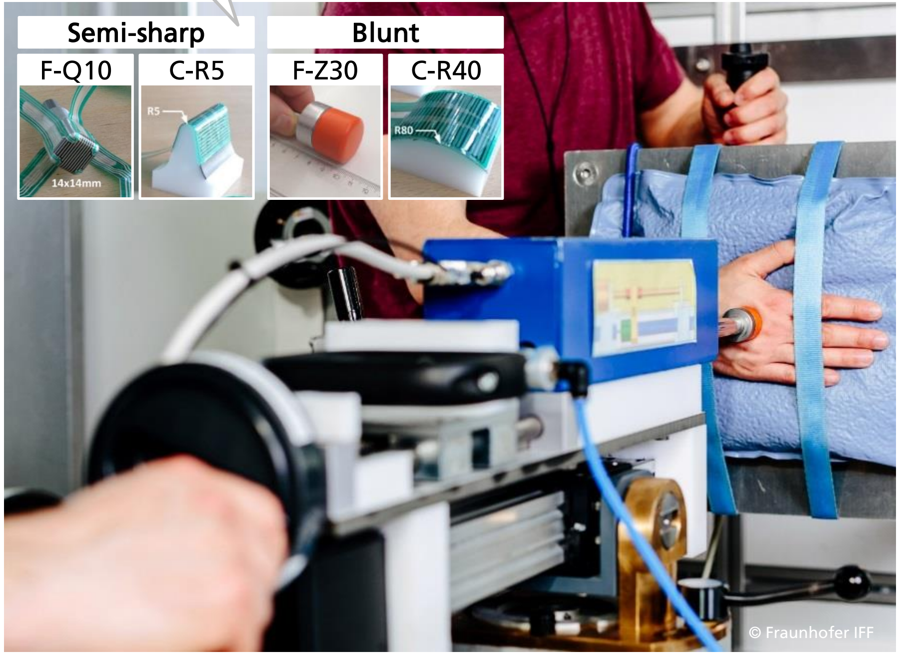
- Manually operated (by a crank handle)
- A thread rod translates rotation of the crank handle to a linear movement
- Impactor can be easily replaced

Procedure

- Force will be slowly increased until the load causes slight pain
- Force transmission is only active when the volunteer presses the three-stage switch to the 2nd stage
- Volunteer releases switch when feeling pain (interrupts force transmission)

used impactors

Quasi-static loads (clamping)



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Methodology
Procedure for transient tests

Principle: impact force is created by the release of the kinetic energy (stored in the pendulum)

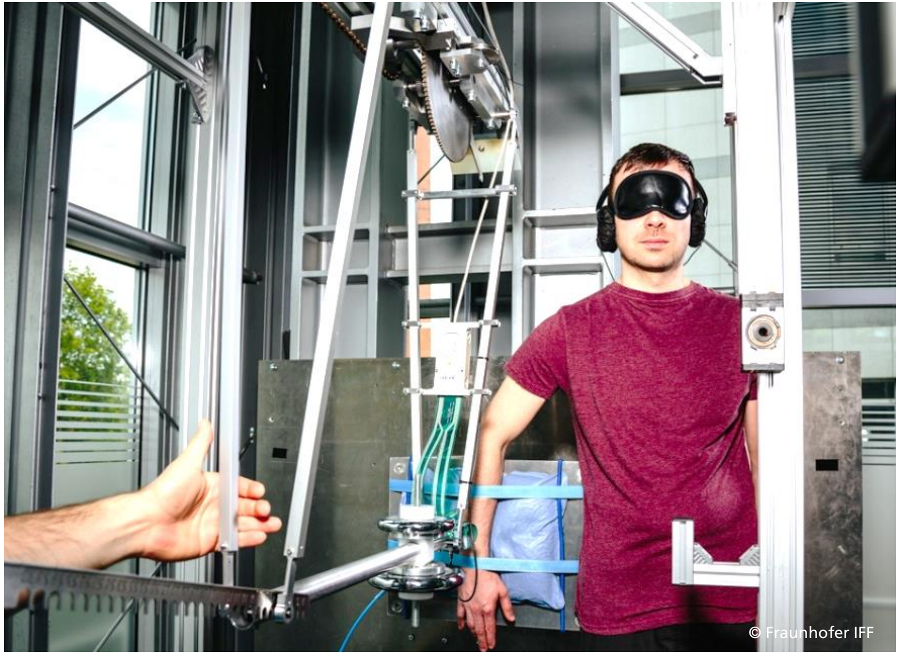
Features of the pendulum

- Manually operated (gradual deflection)
- Each height / pendulum deflection corresponds with a certain impact velocity (up to 1.25 m/s)
- Total weight from 2 kg to 20 kg
- Impactor can be easily replaced

Procedure

- Collision velocity was gradually increased until the impact causes pain / injury (bruise or swelling)
- Idle time between each increase
  - Pain study: seconds
  - Injury study: >7 days

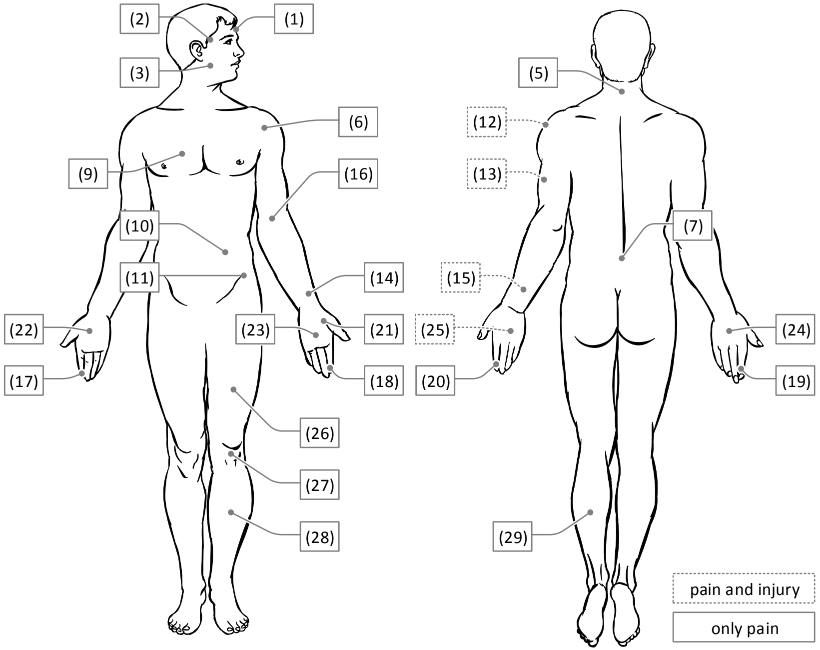
Transient loads (impact)



Results from the pain study
Test plan

control group

	Group	#1	#2	#3	#4	#5
	group size	40	20	20	20	10
Clamping	blunt (F-Z30)	✓				
	semi-sharp (F-Q10)					✓
Impact	blunt (F-Z30)		✓	✓	✓	
	semi-sharp (F-Q10)		✓	✓	✓	
Head	(1) to (3)				✓	✓
Neck	(4)					
	(5)				✓	✓
Trunk	(6) and (7)	✓	✓	✓		✓
	(8) to (11)	✓			✓	✓
Arm and Hand	(12) to (25)	✓	✓	✓		✓
Leg	(26) to (29)	✓	✓	✓		✓



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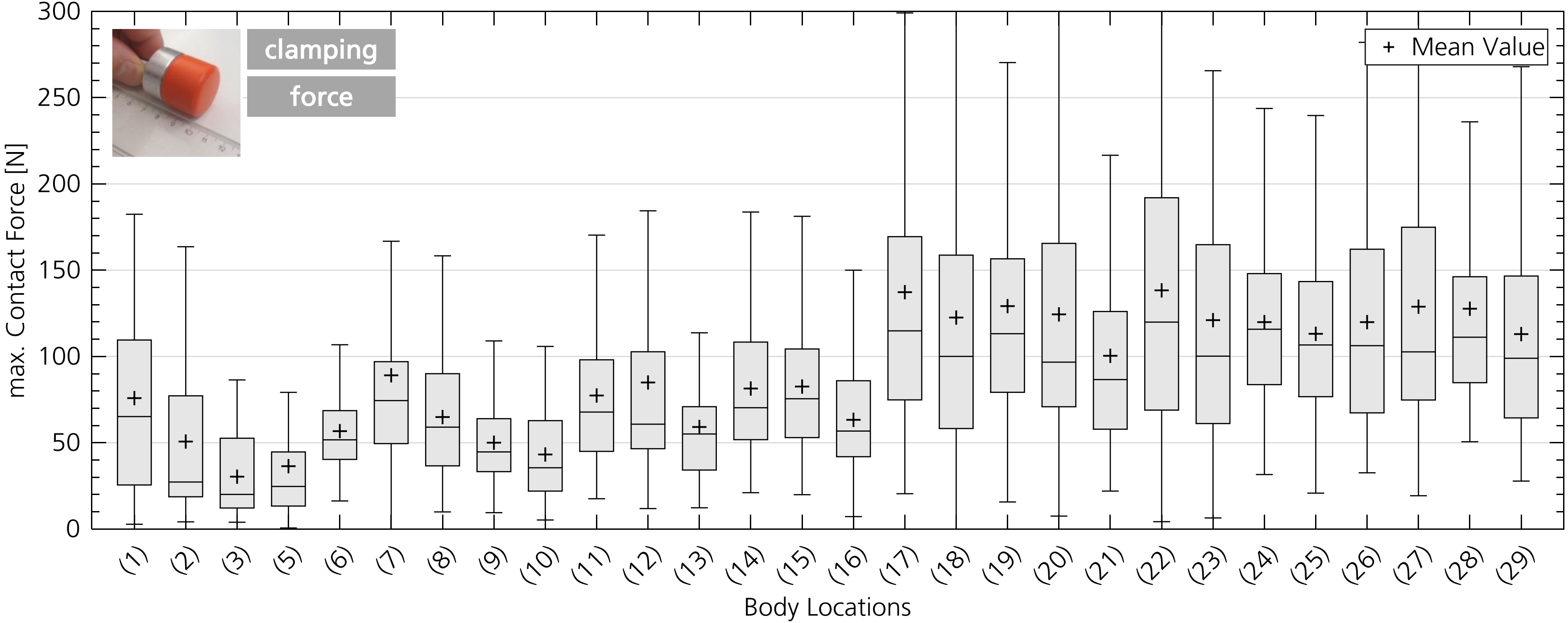
Results from the pain study

Recorded thresholds for blunt clamping (force-based limits)

preliminary results – data analysis has not yet completed



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Results from the pain study

Recorded thresholds for blunt impact (force-based limits)

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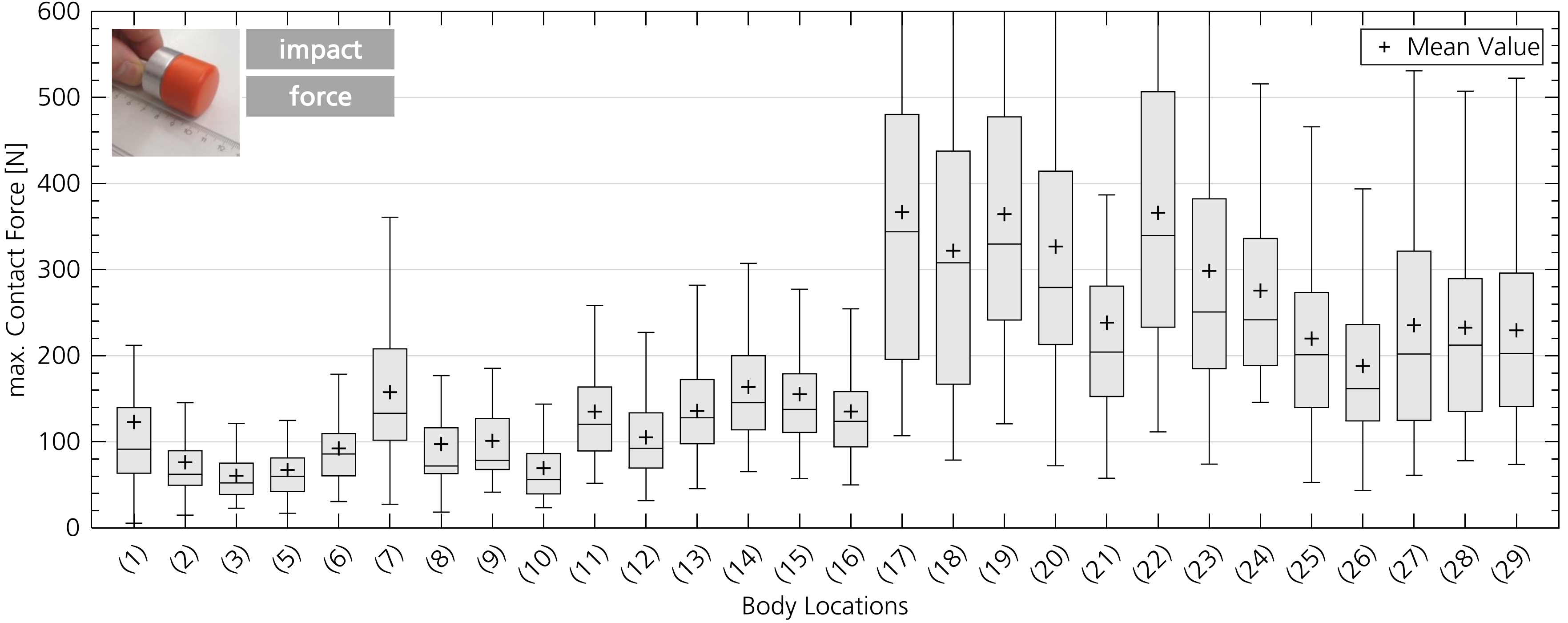

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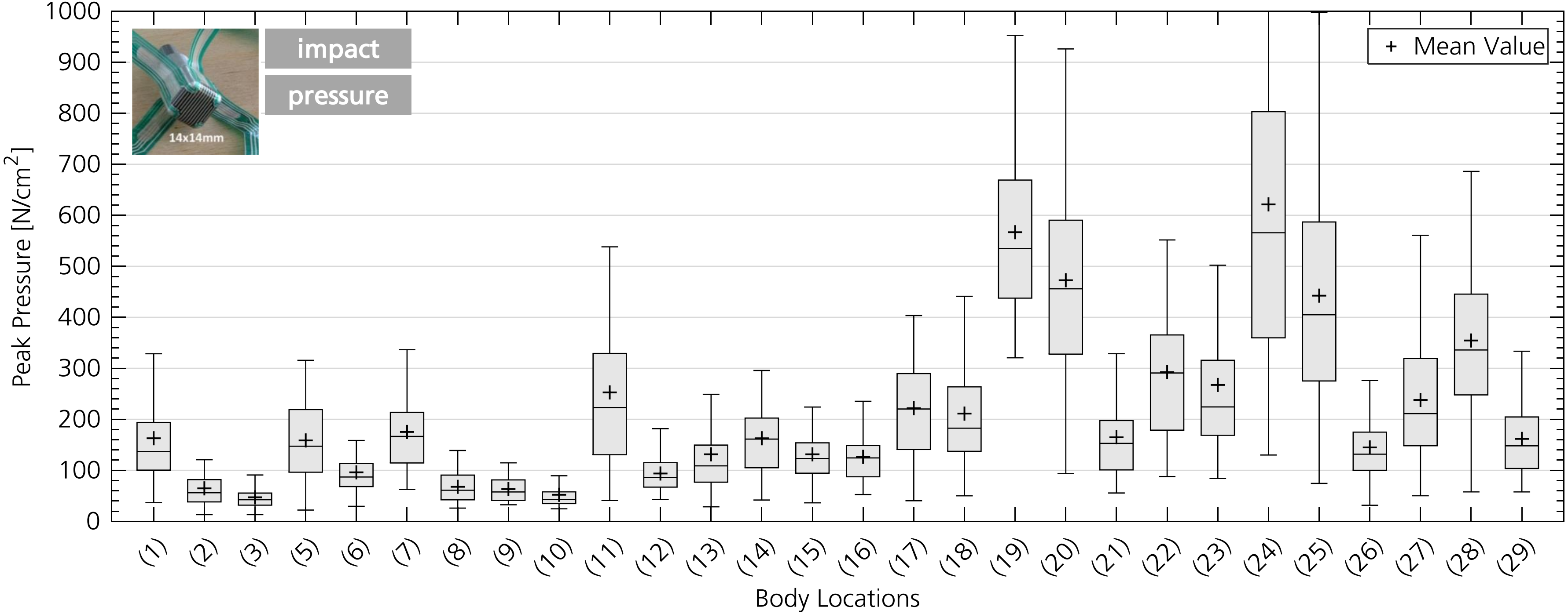
Results from the pain study

Recorded thresholds for semi-sharp impact (pressure-based limits)

preliminary results – data analysis has not yet completed



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Body part	semi-sharp clamping [N/cm²]	blunt clamping [N]	semi-sharp impact [N/cm²]	blunt impact [N]	scaling factors QS → TR: Pressure	scaling factors QS → TR: Force
(1) Forehead	130	110	190	140	1,5	1,3
(2) Temple	110	80	80	90	0,7	1,1
(3) Masticatory muscle	110	50	60	70	0,5	1,4
(4) Neck muscle	140	50	60	70	0,5	1,4
(5) 7th Cervical vertebra	210	70	220	80	1	2
(6) Shoulder joint	160	100	110	110	0,7	1,6
(7) 5th lumbar vertebra	210	90	210	210	1	2,1
(8) Sternum	120	60	90	120	0,8	1,3
(9) Pectoral muscle	170	60	80	130	0,5	2,2
(10) Abdominal muscle	140	100	60	90	0,4	1,5
(11) Pelvic bone	210	100	330	160	1,6	1,6
(12) Deltoid muscle	190	70	120	130	0,6	1,3
(13) Humerus	220	110	150	170	0,7	2,4
(14) Radial bone	190	100	200	200	1,1	1,8
(15) Forearm muscle	180	90	150	180	0,8	1,8
(16) Arm nerve	180	170	150	160	0,8	1,8
(17) Forefinger pad D	300	160	290	480	1	2,8
(18) Forefinger pad ND	270	160	260	440	1	2,8
(19) Forefinger end joint D	280	170	670	470	2,4	2,9
(20) Forefinger end joint ND	220	130	590	410	2,7	2,4
(21) Thenar eminence	200	190	200	280	1	2,2
(22) Palm D	260	160	360	500	1,4	2,6
(23) Palm ND	260	150	310	380	1,2	2,4
(24) Back of the hand D	200	140	800	340	4	2,3
(25) Back of the hand ND	190	160	590	270	3,1	1,9
(26) Thigh muscle	250	170	170	240	0,7	1,5
(27) Kneecap	220	150	320	320	1,5	1,9
(28) Middle of shin	220	150	450	290	2	1,9
(29) Calf muscle	210	110	200	300	1	2

control group

preliminary results – data analysis has not yet completed

significantly high deviations

Mainz [N/cm²]	IFF [N/cm²]	scaling factors: Pressure
130	110	1,7
110	60	1,3
110	30	2
140	30	2
210	70	3,1
160	60	1,8
210	70	3
120	70	1,3
170	60	1,3
140	40	1,5
210	240	1,4
190	90	1,3
220	60	2,5
190	80	2,5
180	60	2,5
180	80	1,9
300	100	2,9
270	80	3,3
280	140	4,8
220	150	3,9
200	60	3,3
260	70	5,1
260	70	4,4
200	170	4,7
190	180	3,3
250	80	2,1
220	130	2,5
220	210	2,1
210	80	2,5

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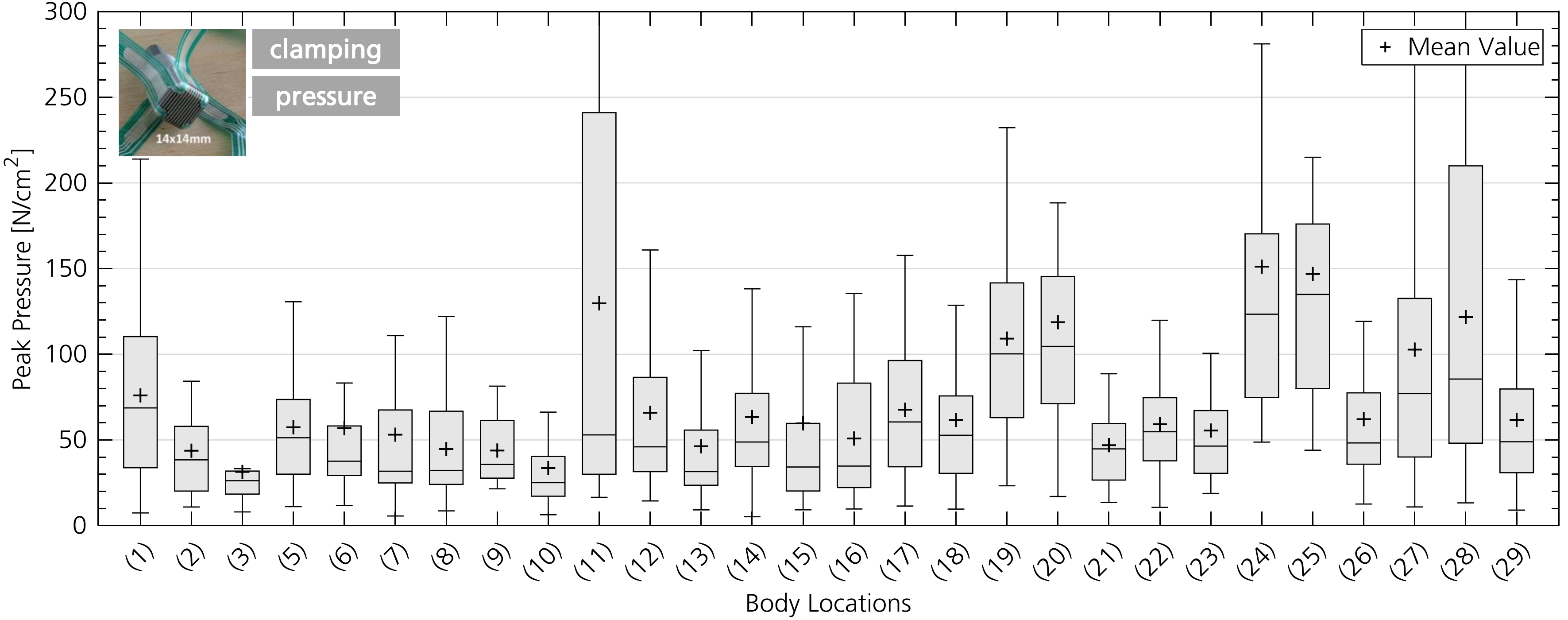
Results from the pain study

Recorded thresholds for semi-sharp clamping (pressure-based limits; control group with 10 subjects)

preliminary results – data analysis has not yet completed



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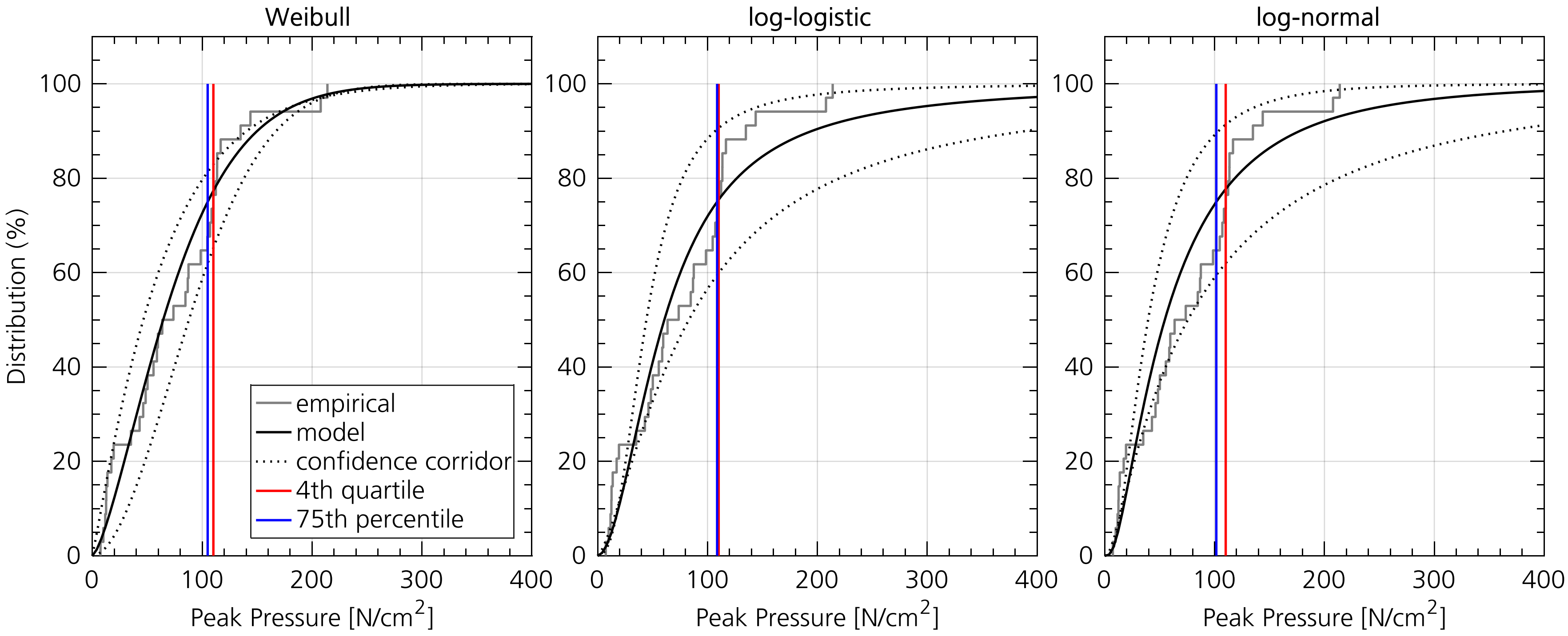
Results from the pain study

Quality of the data from tests with the control group (example shown here: pressure-based threshold for forehead id 1)



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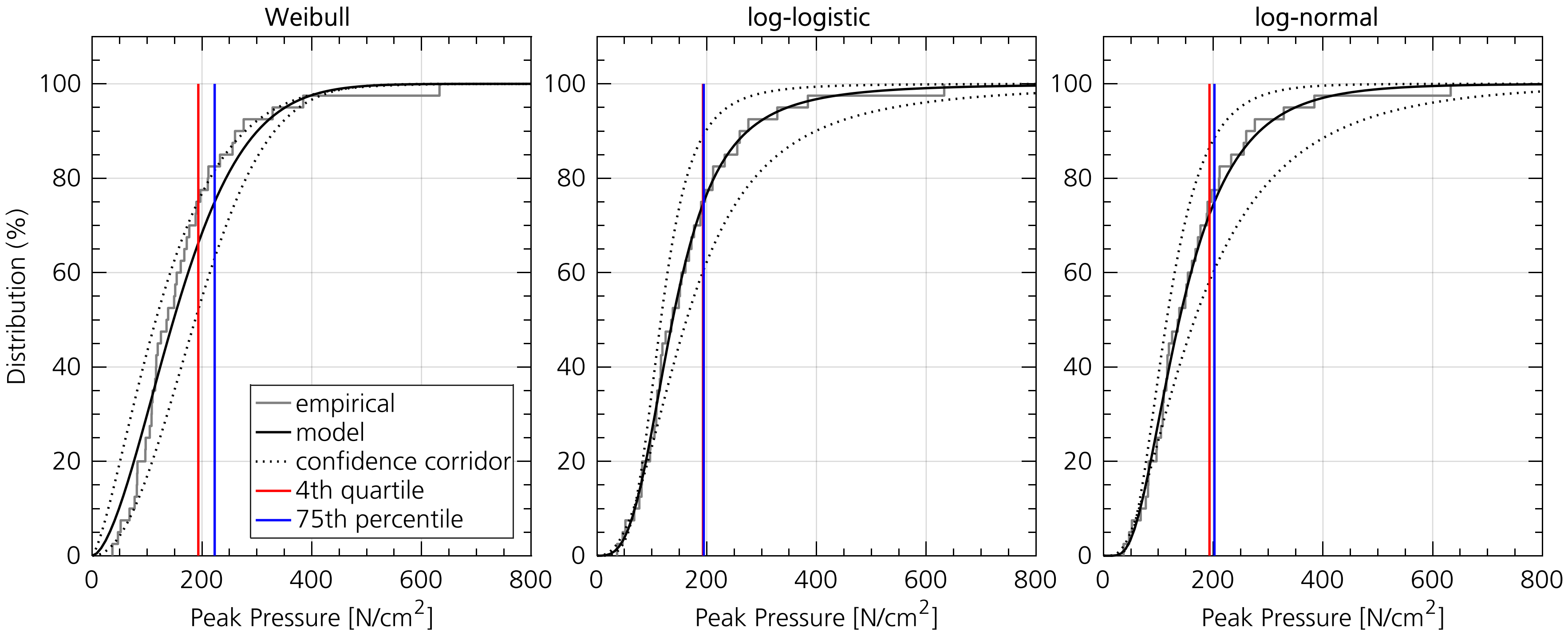
Results from the pain study

Quality of the data from tests with the study group (example shown here: pressure-based threshold for forehead id 1)



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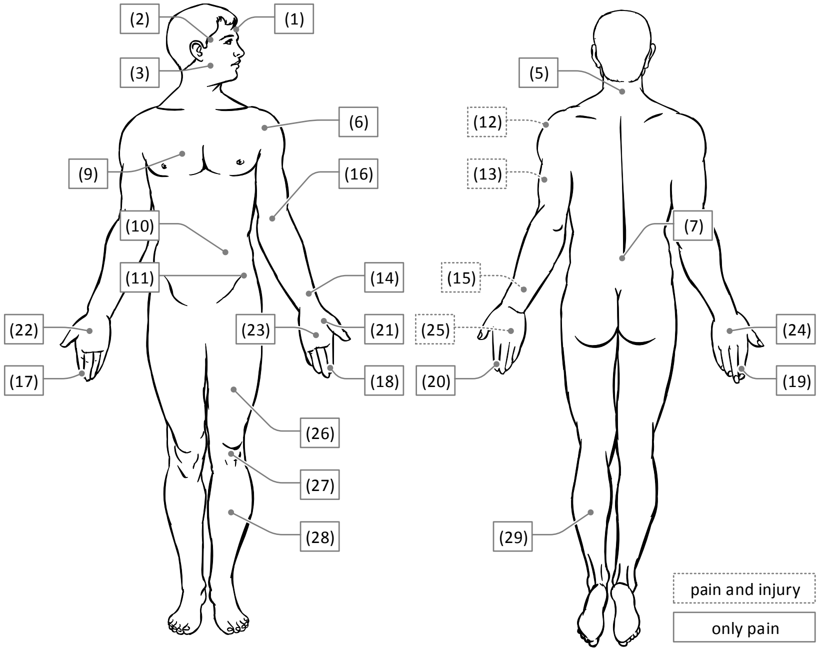
Results from the injury study
Test plan

	Group	#1	#2	#3
	group size	14	4	3
Impact	semi-sharp (C-R5)	✓		
	semi-sharp (F-Q10)		✓	
	blunt (C-R40)			✓
Upper extremities	(12) and (13)	✓	✓	✓
	(15)	✓	✓	✓
	(25)	✓	✓	✓



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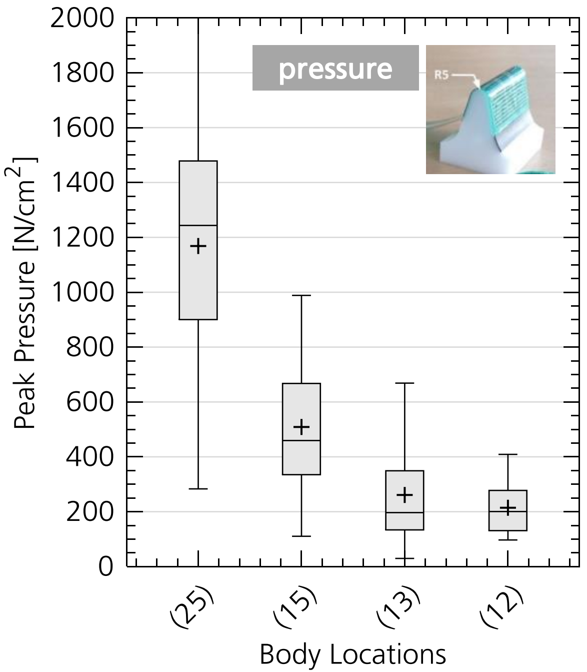
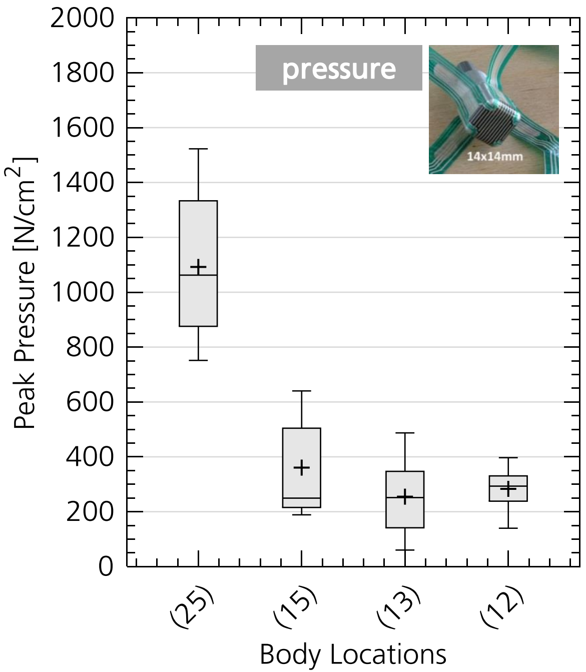
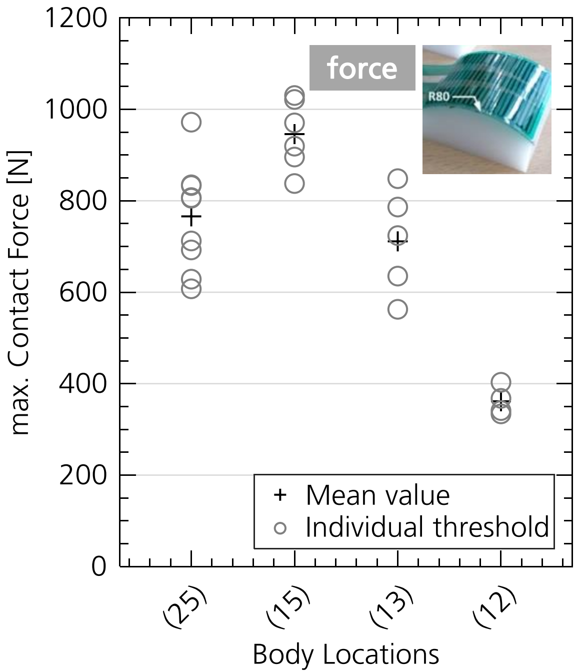
Results from the injury study

Recorded thresholds for semi-sharp and blunt impacts (force- and pressure based limits)







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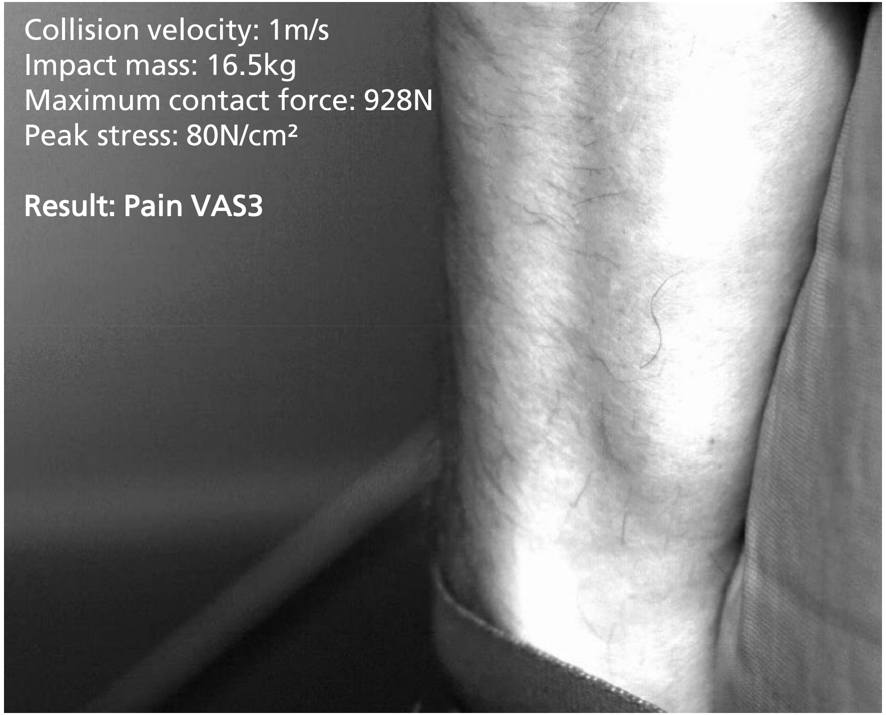
Results from the injury study
Slow-motion footage from the tests



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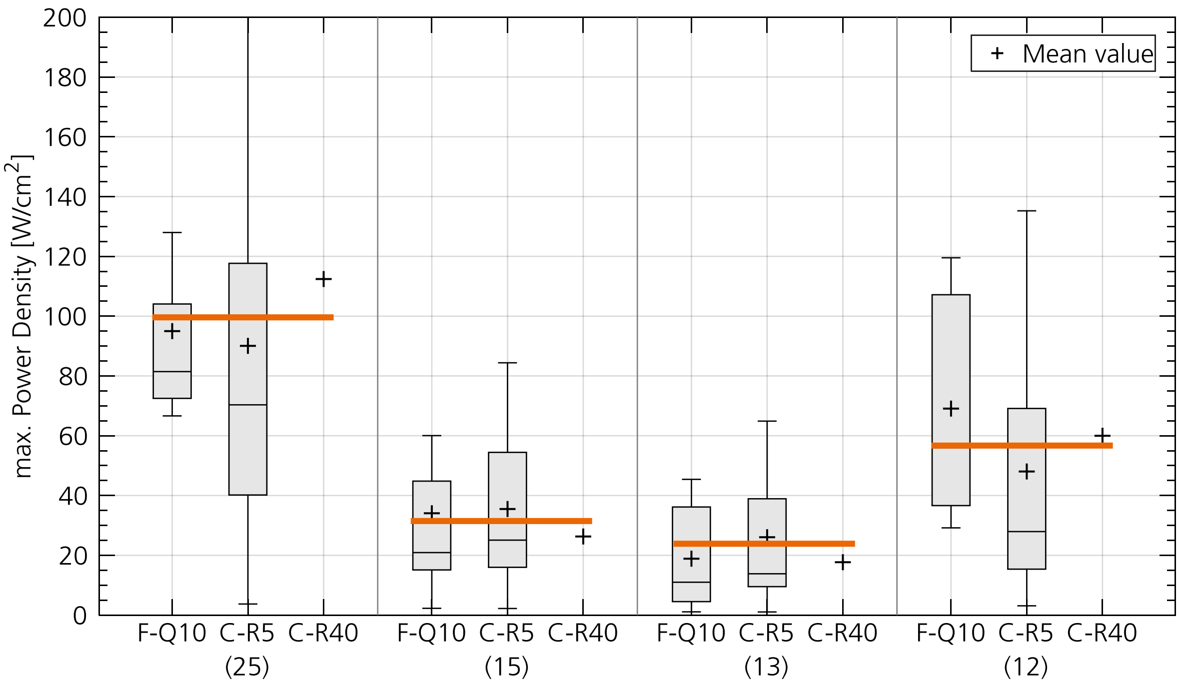
Results from the injury onset study

Injury threshold based on the power density (energy per area and time)



Power density

- Amount of energy …
- Released over a certain area …
- In a certain time

Thresholds based on the power density show an independence from the shape of the impactor

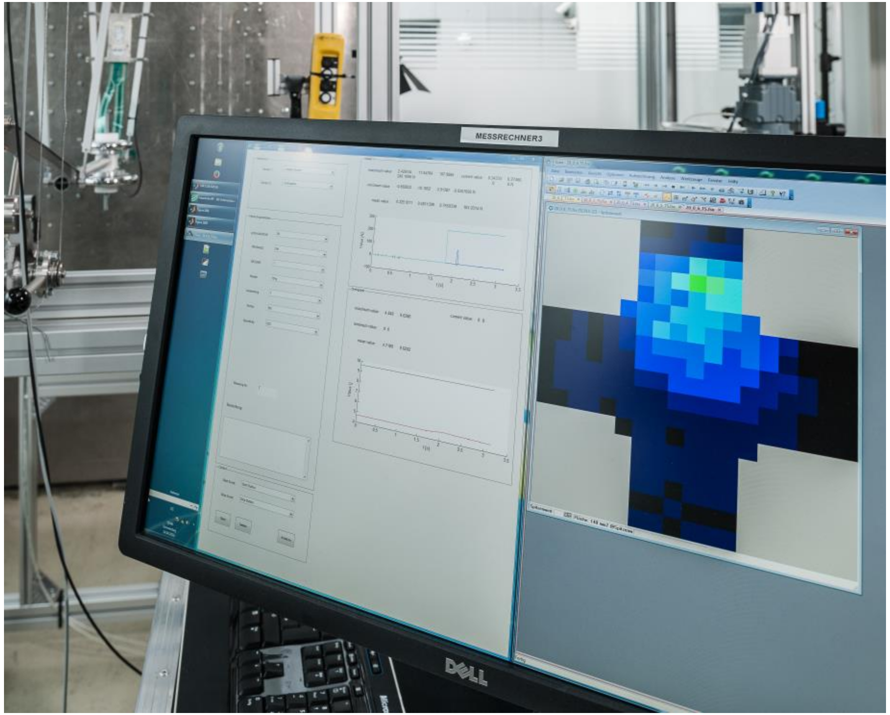
Further findings and observations from both studies

Additional findings from the statistical analysis

- Injury and pain thresholds depend on …
  - Significantly from the gender
  - Moderately from body parameters (age, etc.)
  - Slightly from the impact mass
- Impact energy and absorbed energy have a significant correlation
- Power density seems to be the only quantity which is independent from the contact shape

Made observation

- Visual examination leads to false-negative results (MRI is more reliable)
- The force- and pressure-based thresholds for pain exceed those for injury



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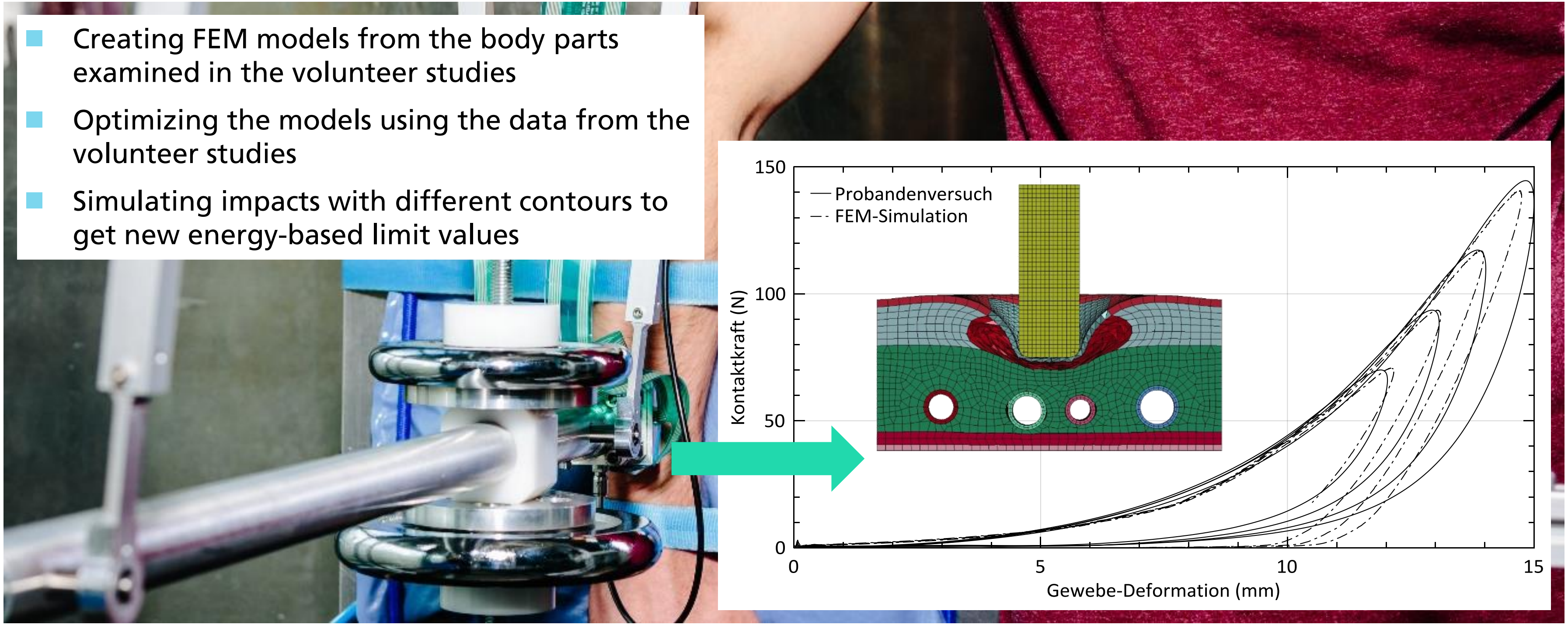
Ongoing work
FE-based model to simulate human-robot collisions

- Creating FEM models from the body parts examined in the volunteer studies
- Optimizing the models using the data from the volunteer studies
- Simulating impacts with different contours to get new energy-based limit values



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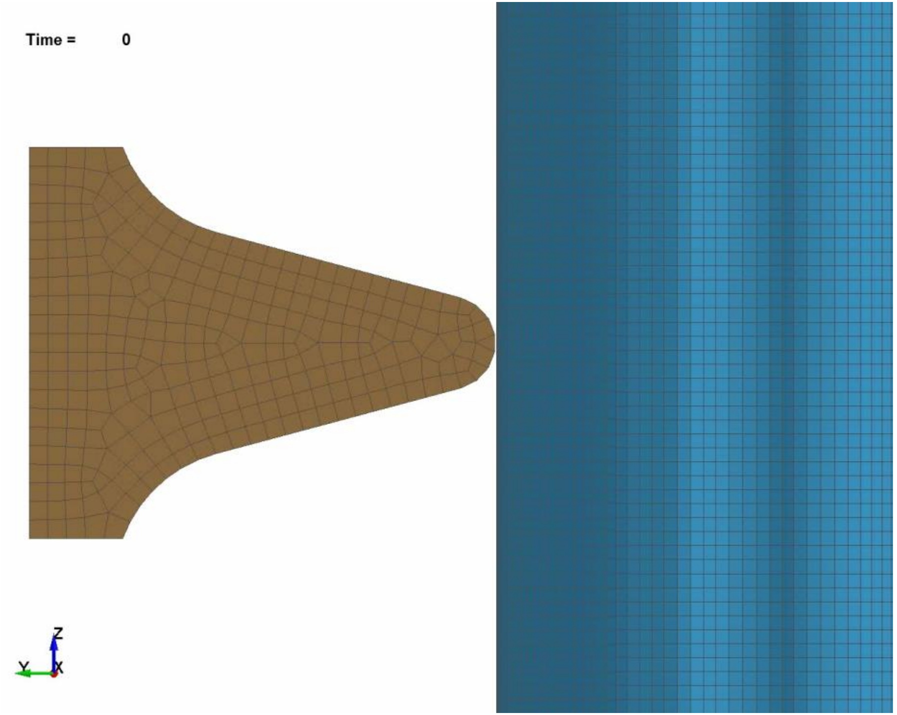

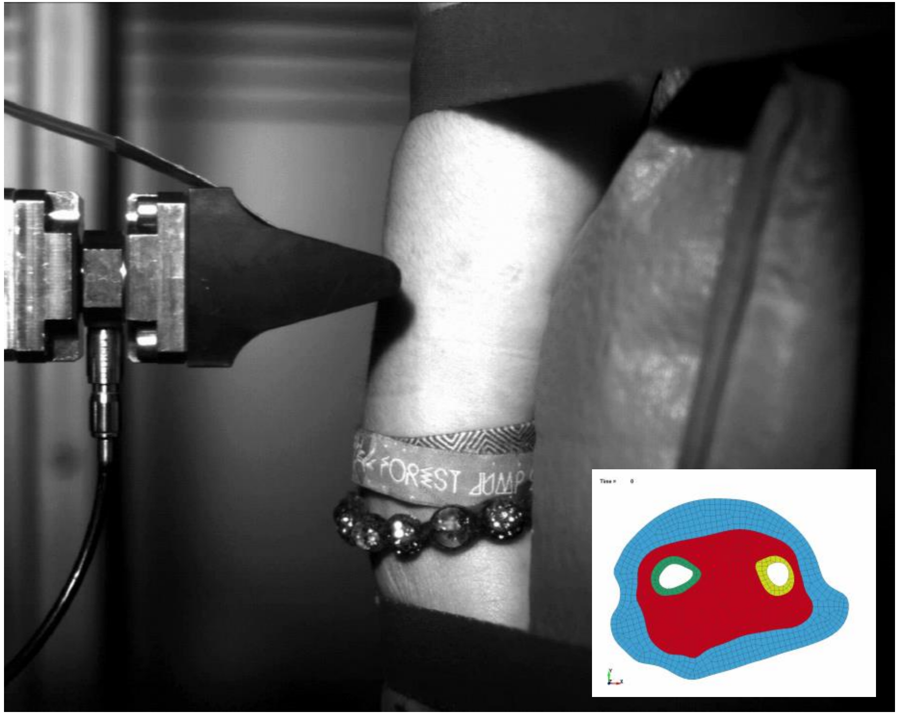

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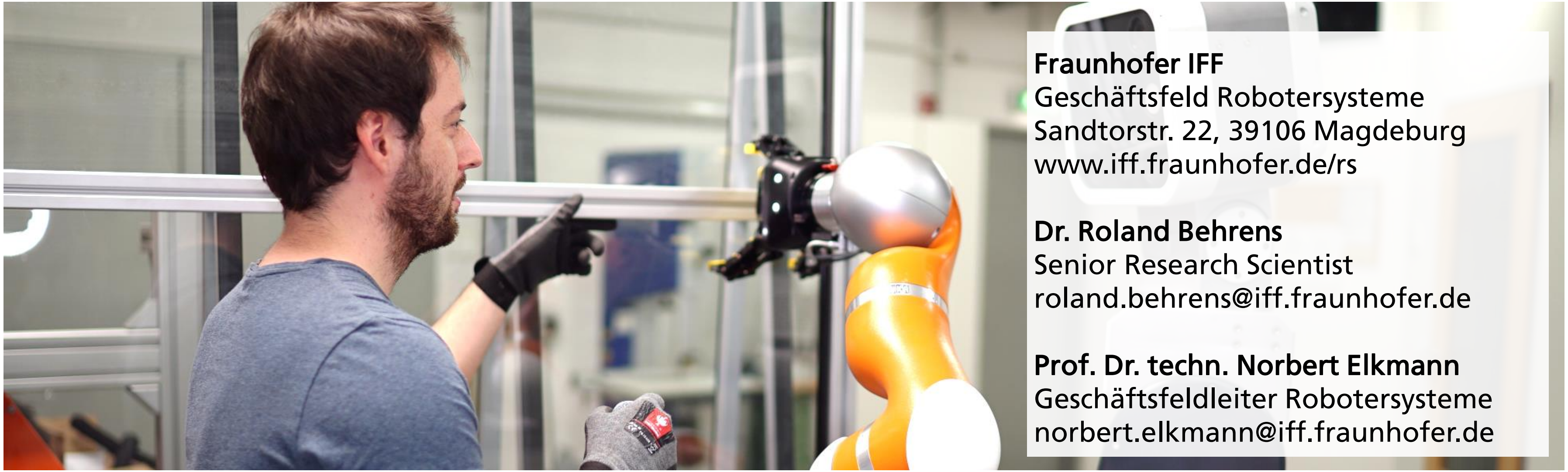

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