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Study on meaningful and verified Thresholds for minimizing the Consequences of Human-Robot Collisions

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Abstract— **In order to define meaningful limit values for human-robot collisions, we have come to the conclusion that only comprehensive collision tests with live test subjects will successfully lead to verified limit values. A literature survey about current approaches for limiting the consequences of hazardous contacts between humans and moving machines (including robots) showed that limit values are often specified without an appropriate injury severity or without considering the variety of the human body. In this article, we show why the injury onset is appropriate to limit the consequences of human-robot collisions, and how this onset can be quantified through collision tests with live test subjects. With our work we would like to present a promising method that can remedy the current lack of consensus regarding an appropriate injury severity and verified limit values.**

I. Preface

Industrial workplaces with physical Human-Robot Interaction (pHRI) have been increasing recently. In general, such settings pose a significant risk for the human's health, since collisions with the robot cannot be avoided completely. In the last decade, collisions between robots and humans were studied in various experiments and simulations. The most comprehensive studies were carried out by the German Aerospace Center (DLR), which, for instance, analyzed the characteristics of human-robot collision through experiments with crash-test dummies [1] [2] [3] [4]. Other research groups, which are also noteworthy in this context, used stress tests with live test subjects to study the maximum operation conditions of collaborative robots in order to limit the consequences of unintended contact on pain-related levels [5] [6].

In accordance to these studies, we have come to the conclusion that only comprehensive stress tests with live test subjects will successfully lead to verified limit values. In this article we will present a new approach on how blunt impacts can be quantified by performing experimental collision tests with live test subjects, and, therefore, how a specific threshold can be provided with verified limit values. This is an extension of our previous activities in the field of human-robot collisions whereby we analyzed the correlation between constrained and unconstrained impacts [7]. During this study we developed an experimental test-rig that allowed for performing collision test with live test subjects. As we will show later, this set-up was used in our present work to quantify critical thresholds for blunt robot-human collisions.

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In Section II we give a brief overview of the most recent approaches for determining appropriate thresholds that define the maximal consequences of hazardous contacts with moving machines like collaborative robots. In Section III we introduce the field of blunt impact injuries in order to provide an understanding of this field, their related effects, and the processes involved. The experimental design, methodology, and first results of our study are presented in Section IV. Finally, we conclude our work in Section VI and give a brief outlook regarding our further work on this topic.

II. Collisions and their Allowable Consequences

There are several approaches for defining the allowable consequences of hazardous contact situations between humans and moving machines. In this chapter we summarize the most recent approaches and their corresponding limit values. Our solution to overcome the gap between verified limit values and a corresponding injury severity is then presented in the last part of this section.

A. Critical consequences of collisions in pHRI

The discussion about the critical consequences of an impact in robotics arose as the demand for pHRI in manufacturing has increased. There are currently a variety of different notions on what critical or still-allowable consequences of contacts between humans and robots could be and there is no clear consensus. The most common approaches are summarized below.

Pain: The pioneering work of Yoji Yamada introduces the pain tolerance limit as the critical stress for humans which may arise during a collision with a robot [5]. A similar approach is followed in [6]. The pain entrance level is currently examined by the University Medical Center of the Johannes Gutenberg University Mainz (JGU Mainz) in a current study that was initiated by the German employers' liability insurance association (BG). In this study the pain onset of 100 subjects is being examined at 29 well-distributed body locations through the use of a pain algometer [9]. Note, that pain entrance is different from pain tolerance. Pain entrance expresses the minimum stimulus inducing pain, while pain tolerance refers to the maximum intensity of stimulus tolerated [8].

Injury: The Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA) recommended that all injuries can be considered as acceptable if the severity doesn't exceed a contusion without skin opening and fractures as included by AIS1 of the Abbreviated Injury Scale or superficial injuries of the ICD-10 classification [10]. A similar approach was presented by the

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DLR that considers a contusion without skin opening as appropriate for human-robot collisions [11]. A precise specification of this trauma is provided by the AO Classification for fracture description of the human skeleton.

B. Limit values of collisions in pHRI and machinery safety

In order to limit the consequences of unintended and hazardous contacts to machines on a specific level, independently of what is finally considered as acceptable, the introduction of biomechanical and/or operational limit values is necessary. The most recent limit values are summarized below.

Standards: There are several standards about machinery safety, which are specifying limitation quantities to minimize the injury risk of mechanical hazards like collisions. The most frequently used quantities and their associated values are summarized in Table I. As the summary shows, most of the reviewed standards define neither an injury severity nor a body location for the specified threshold values. Furthermore, there is no information whether the specified values were verified or not.

Pre-standards: A standard on testing body impact protection equipment, that has currently draft status, differentiates between severe and slight injuries. A total of eleven body regions are taken into account for which, depending on the injury severity, specific force limit values are provided. The limit values were gathered from literature of different research sectors and first published in the HSE report RR906 [20]. Another detailed list of biomechanical limit values can be found in a recommendation of the IFA [10]. In contrast to all other references, this list is set up in a highly differentiating manner by regarding force and pressure as relevant quantities for limiting the effects of collisions. Furthermore, a well-structured body model is used to allocate three specific limit values for each of 15 body regions. The authors gathered all values from a comprehensive literature survey.

TABLE I. INJURY SEVERITIES AND THRESHOLDS IN STANDARDS

Source →	[12] [13]		[12]	[14] [15]	[16]	[17]	[18]	[19]
Injury Severity →	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Quantity →	energy	force	pressure	force	force	force	force	force
Body Part					[N]	[N]	[N]	[N]
skull / forehead	4J (permanent contact) 10J (temporary contact)	75N (permanent contact) 150N (temporary contact)	25N/cm² (permanent contact) 50N/cm² (temporary contact)	400N for 0.75s to 150N for 5s to finally 25N OR only 50N	400	250	150	50
face								
neck (sides / neck)								
neck (front / larynx)								
back / shoulders								
chest								
belly								
pelvis								
buttocks								
upper arm								
lower arm								
hand / finger					150			
thigh / knee					400			
lower leg								
feet / toes / joint								

Robotic research: The focus in the most-recent work of the DLR [11] was not about which values cause specific injury, but rather about the parameters of moving rigid objects. Here the parameters velocity, reflected mass and shape of the contact area are taken into account. In a variety of drop tests, speed limiting functions were determined by using porcine abdomen flesh, which has characteristics similar to human abdomen tissue. The result shows a clear dependency between injury severity and the parameters of the dropped impactor.

TABLE II. INJURY SEVERITIES AND THRESHOLDS IN PRE-STANDARDS

Source →	[20]	[10]	
Injury Severity →	Slight/ None	Minor (AIS1)	
Quantity →	force	force	pressure
Body Part	[kN]	[N]	[N/cm²]
skull / forehead	<1	175	30
face	<0.1	90	20
neck (sides / neck)	<0.1	190	50
neck (front / larynx)		35	10
back / shoulders	<2	250	70
chest	<0.5	210	45
belly	0.8...2	160	35
pelvis		250	75
buttocks		250	80
upper arm	1.7	190	50
lower arm	0.5	220	50
hand / finger		180	60
thigh / knee	1...5	250	80
lower leg	<1	170	45
feet / toes / joint	0.13...1.3	160	45

All limit values summarized in Table I and II, have one essential disadvantage in common: their validity was never verified with living humans. Neither single subject tests nor tests with high statistical significance were carried out. Thus there is no certainty regarding the correlation of the defined collision consequences (if defined) and their related limit values. In our opinion the lack of unverified limit values is the main reason why none of all available approaches and their limit values were adopted for pHRI, and, therefore, safety in pHRI will remain an uncertain issue.

C. Approach and contribution of our work

The available approaches for classifying the allowable consequences of hazardous contacts range from using pain entrance to minor injuries, which, for instance, can be classified by AIS1, as criteria. We expect that the pain onset is not a suitable measure to define threshold values since it will provide significantly low force and pressure values, which would further result in slow and less useful robot velocities. On the other hand we consider minor injuries as classified by AIS1 to be too severe, since AIS1 includes per definition, a mortality rate of 7‰ and one broken rib [21]. In our opinion, neither the former nor the latter injury is acceptable in the sense of pHRI. The pain tolerance level introduced by Yoji Yamada [5] seems to be a promising approach that should be further pursued. However, it is not clear whether a serious correlation between pain tolerance and injury exist or not. In this case there is only one of the presented severity approaches left: mild contusions without skin opening and without fractures. In order to accept this as the allowable injury severity for human-robot collisions, it is crucial to limit their degree according to a number of concrete phenomena. We discussed this issue intensively with experts for occupational safety and physicians from different specialist areas. We concluded that the acceptable degree should only appear as an edema (commonly known as a bump) and a bruise, which can be, from a medical perspective, considered as harmless, since the healing process of these injuries generally ends without permanent consequences.

Although biomechanical research focuses a great deal of attention on human tolerance testing, almost no substantial information could be found in the area of contusion thresholds. Only one article was found that gives insights into contusions and their formation due to dynamic impacts [22].

III. Blunt Impact Trauma

In medical terminology, a hazardous collision between humans and blunt objects that causes injuries without skin penetration is denoted as a *blunt impact trauma*. The appearance of injuries resulting from blunt impact trauma is determined by the physical characteristics of the moving object which collides with the human body, and the specific body location. The resulting injury is in part due to the ability of the moving object to displace tissue with high velocities. The substantial injury causing factors are the total amount of energy discharged, the time in which the energy is discharged, and the area over which the energy is released [23] [24].

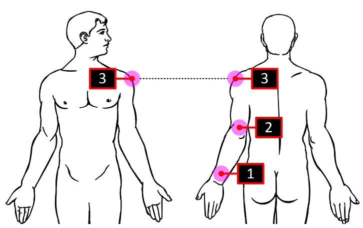

Figure 1. Selected locations for examination of mild contuison thresholds

The typical phenomena of mild contusion are edema and bruises, whose appearance essentially depends on the intensity of the blunt force trauma. The initial reaction to blunt trauma impact is dilatation of capillaries that further reduces the flow of blood. In addition, the permeability of the capillaries increases whereby plasma passes into the traumatized tissue and fibrin occludes the lumen of lymphatics. These processes result in the swelling of the traumatized localization. When the impact intensity is higher, both in terms of force and/or energy discharged, the underlying blood vessels are lacerated microscopically and a visible bruise forms. The appearance of the bruise is determined by the amount of bleeding, the type of tissue, the depth at which the bleeding originates, and the time of clotting. Typically, both the dermis and the subcutaneous tissue, with possible extension into superficial layer of muscle, are affected through the impact [23] [24] [25].

As shown by the DLR, a collision with a complex robotic system can be reduced to a rigid object that is characterized by the parameters *velocity* v_0, *mass* m, and *surface shape* S [11]. These parameters can be considered as relevant injury-causing factors. According to [22] further quantities including *maximum contact force* F, *maximum pressure* ρ, *impulse* p, *absorbed energy* $\Delta W$and *density of the absorbed energy* $d_{\Delta W}$ should also be considered, because it is not yet clear if these quantities have an essential influence on blunt impact trauma.

IV. Experimental Design

This section provides all information about the experimental design including the setup, used methods and the medical accompaniment.

A. Ethics

Ethical approval for this study was obtained from the Ethical Committee of the Otto von Guericke University in Magdeburg. The study was deemed acceptable since the impact tests have “minimal risk”. The experimental set-up and the continuous medical accompaniment of our study were important factors in obtaining the positive evaluation.

B. Subjects

For the preliminary phase of the study we selected three locations on the left arm for examining collision as shown in Figure 1. These locations are the most exposed parts of the human body and therefore, have a high probability of being involved in a collision. Altogether we acquired four subjects (one female, three males, age 28.8 ± 2.1, weight $(73.3 \pm 5.8)\,\mathrm{kg}$, height $(1.79 \pm 0.05)\,\mathrm{m}$).

C. Experimental setup

The experimental setup is illustrated in Figure 2. It consists of a coupled pendulum hanging from a stiff frame $\{1\}$. In front of the frame, a stiff rack $\{2\}$ is installed to fasten the body parts of the subjects before inducing impacts. Additional fixing devices $\{3\}$ and a vacuum mat $\{4\}$ are used to keep the subjects in position and to minimize evasive movements. The pendulum body itself consists of a ram $\{5\}$ and an impactor $\{6\}$ located on the front side. Altogether, three impactors of different shapes are available as shown by Figure 3. A mounting device is provided to increase the effective mass $\{7\}$ of the ram body in discrete steps. In the preliminary phase of our study we used only two different masses. Each mass includes the permanent weight of the pendulum ($\approx 1.36\,\mathrm{kg}$) and additional weights that were mounted on the ram. In order to determine the exact pendulum inertia, we carried out an experiment where the oscillating motion of the loaded pendulum was measured. Afterwards, the pendulum parameters, namely inertia and damping coefficient, were determined by fitting a model of the pendulum on the measurement acquired in the oscillation experiment. This approach yields for both masses $4.16\,\mathrm{kg}$ and $8.65\,\mathrm{kg}$ respectively, which are typical for small collaborative robots like the LWR of the DLR [24]. A locking mechanism $\{8\}$ at the back side of the pendulum frame is provided to fix and release the deflected ram. The maximally adjustable deflection corresponds with a collision velocity of approximately $1.25\,\mathrm{m/s}$.

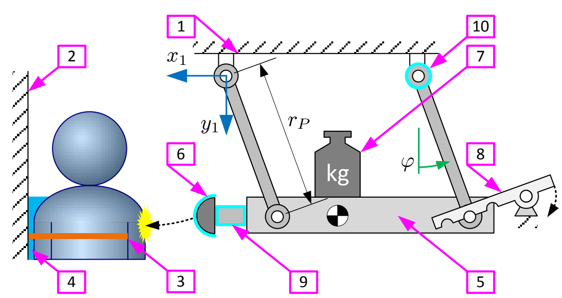

Figure 2. Experimental set-up with all relevant components

A piezo-electric load-cell is used to measures the impact force. The pendulum angle deflection is measured by a precise potentiometer $\{10\}$ mounted on a linkage joint. Both signals are sampled with $f_S = 10\mathrm{kHz}$ and a resolution of $16\mathrm{bit}$. All all impactors are covered with a pressure sensor from TekScan {3} that samples at a rate of $f_S = 1.3\,\mathrm{kHz}$.

D. *Experimental methods*

Collision tests with different impact energies (mass and collision velocity are adjustable) and impactor shapes are the key elements of our work for determining the threshold of mild contusions. Our approach includes the application of impact energies upon selected body locations until a critical consequence occurs, in particular the appearance of an edema or a bruise, and the perception of intolerable pain. The pain tolerance level must be taken into account, because it is not ethically acceptable to subject the volunteers above theirs individual pain tolerance. During a collision test all relevant quantities (the contact force, the pressure within the contact area and the pendulum motion) are measured.

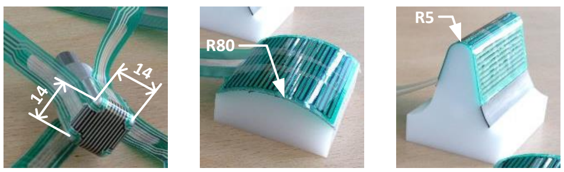

Figure 3. Available impactors

The entire experimental procedure is illustrated in Figure 4. Note that any initial session will always start with the highest mass as highlighted green in the illustration. This allows for a systematic coverage of the available energy spectrum with a minimal number of sessions. Whenever a critical consequence occurs and there are still available masses left, it is necessary to wait fourteen days until the stressed body part is healed and therefore the examination can be continued [25]. Otherwise, without any injury-related evidences, a relaxation time of seven days is considered as sufficient. The collision velocity is given by the deflection of the pendulum and the position when the pendulum collides with volunteer. Since it is hardly possible to position the volunteer in front of the pendulum so that the impact is induced at the zero crossing point of the pendulum $\varphi = 0$, the collision velocity cannot adjusted on specific values precisely. Figure 5 shows the real test-rig and a collision test.

E. *Medical accompaniment*

Each subject needed to pass a comprehensive assessment of their physical condition that was conducted by trauma surgeons, which are highly experienced in the effects of cardiovascular disorders. They took an anamnesis and evaluated essential body functions such as clotting time, heart rhythm, sense of balance, etc. Only when no health-related concerns and risks were diagnosed, were the respective subjects considered acceptable for the study. Furthermore, ultrasound images of the selected target locations were recorded by dermatologists in order to document the initial state.

A physician is present the entire time during a collision test to ensure quick initiation of medical countermeasures should any complications arise. Directly after the collision test the stressed body part of the subject is examined and photographically documented. Meanwhile, the subject recorded its sensed pain on a five-step perception scale. All diagnostic results will be documented in a report. This short examination is followed by another one, which takes places six hours after the collision test. This waiting time corresponds to the time period in which any possible swelling would appear [25]. During the follow-up examination a visual and ultrasound diagnosis of the stressed body locations was made.

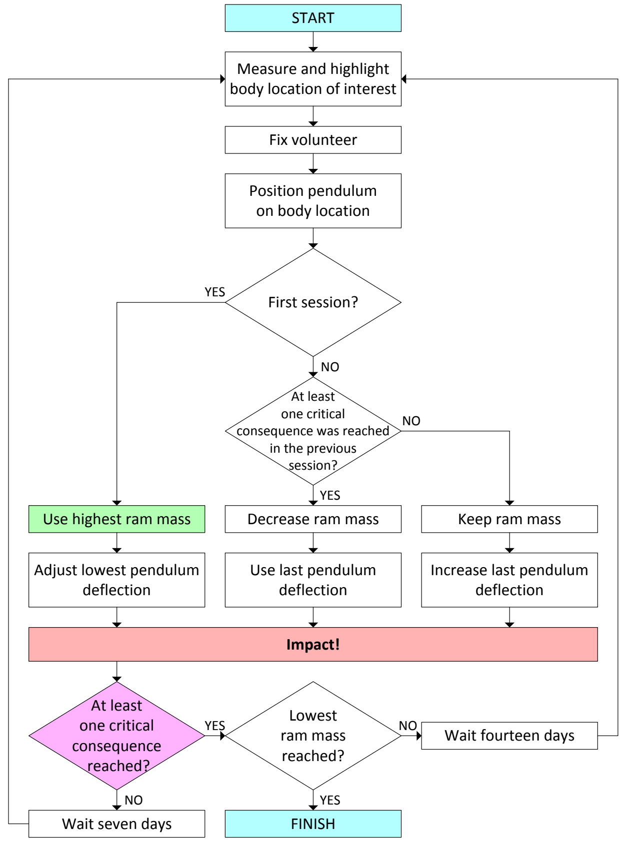

Figure 4. Experimental procedure for examinig a specific body location

Figure 5. Pendulum (left) and the examintation of a volunteer (right)

The medical accompaniment was carried out by the Medical Center of the Otto von Guericke University in Magdeburg (Germany), in particular by physicians from the Institute for Forensic Medicine, the Clinic for Accident Surgery, the Clinic for Dermatology and Venereology, and the Institute for Neuroradiology.

V. Results

For the preliminary phase of our study we carried out collision tests with four subjects on three body locations. The measurement and medical results of these tests will be presented in this section.

A. Measurement data evaluation

The acquired measurement data were analyzed as follows. The collision velocity v_0 was computed from the position signal $\varphi(t)$ of the pendulum. Here, the collision velocity is defined by the time when physical contact between impactor and subject occurred $t = t_0$ and, therefore, the contact force rose

$$v_0 = r_P \dot{\varphi}(t_0) \qquad\qquad F(t \geq t_0) > 0, \tag{1}$$

While r_P denotes the radius of the pendulum. The peak force $F_{\max}$ is given by

$$F_{\max} = \max\{F(t)\}. \tag{2}$$

The maximum pressure $\rho_{\max}$ within the contact area was directly acquired by the TekScan system. A typical contact pressure image is shown by Figure 7 in the appendix. The impulse p can be determined by computing the integral of the contact force during the interval $[t_0 \ldots t_e]$ in which the contact was present

$$p = \int_{t_0}^{t_e} F(t)dt. \tag{3}$$

As discussed in [22] the energy which is absorbed by the stressed tissue during the collision may have an essential influence on injury as well and, therefore, on the occurrence of bruises and/or critical pain. The area within the force-compression hysteresis must be computed in order to get the absorbed energy

$$\Delta W = r_P \int_{\varphi(t_0)}^{\varphi(t_e)} F(t)d\varphi \qquad d_{\Delta W} = \frac{\Delta W}{\max\{A_\rho(t)\}} \tag{4}$$

where A_ρ denotes the contact area acquired by the TekScan system. The results of the most relevant results are summarized in Table III, while Figure 7 shows the related force curves.

B. Medical examination

During the collision tests, two subjects developed a visible bruise at location {2} (upper arm). At the same location one subject got a bruise and remarked that the perceived pain reached his/her tolerance level denoted by a value of 5 within a pain scale from 1 (no pain) to 5 (intolerable). The pain tolerance level of 5 was reached at the locations {1} (lower arm) and {2} (upper arm) in three separate tests. At location {3} (shoulder), none of the participating subjects have yet to reach their pain tolerance levels or have been bruised.

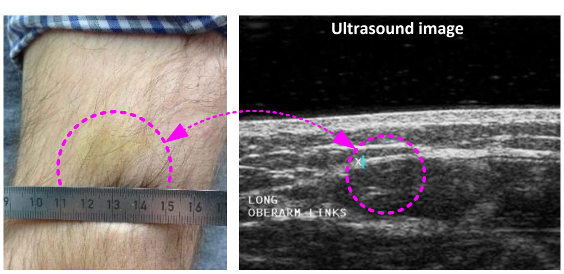

Figure 6. Bruise on the upper arm (male subject, age 30, 81kg, 1.86m)

The ultrasound examination was accomplished after each session at all stressed body locations in order to diagnose a subcutaneous edema and/or bruise. Unfortunately, we came to the result that the resolution of the available ultrasound scanner is insufficient for identifying slight bruises and edemas clearly. One bruise, which could be diagnosed by ultrasound, is shown in Figure 6.

TABLE III. RESULTS OF THE PRELIMINARY PHASE

#	Subject	Location	Impactor	m [kg]	Stress result[1]	v_0 [m/s]	$F_{\max}$ [N]	$\rho_{\max}$ $\left[\frac{N}{cm^2}\right]$	p [Ns]	ΔW [J]	$d_{\Delta W}$ $\left[\frac{J}{cm^2}\right]$
1	1	1	R5	8.65	-	0.64	351	213	8.73	1.4	0.45
2	1	1	R5	8.65	PTL	0.74	447	*[2]	9.99	1.7	*
3	1	2	R5	8.65	B	0.83	393	208	10.83	1.9	0.46
4	1	2	R5	8.65	PTL, B	0.94	523	277	12.6	2.1	0.5
5	1	2	R5	4.16	-	0.83	212	111	4.3	5.14	0.68
6	1	3	R5	8.65	-	1.18	269	153	14.74	5.2	2.13
7	2	1	R5	8.65	-	0.64	421	306	8.57	1.5	0.51
8	2	1	R5	8.65	PTL	0.74	438	*	9.66	2	*
9	2	2	R5	8.65	-	0.71	327	201	9.65	1.9	0.7
10	2	3	R5	8.65	-	1.25	291	85	16.25	5.6	4.05
11	3	1	R5	8.65	-	0.63	379	256	8.42	1.2	0.47
12	3	2	R5	8.65	-	0.63	283	222	8.61	1.5	0.7
13	3	3	R5	8.65	-	1.07	312	*	13.32	4.5	*
14	4	1	R5	8.65	-	0.45	211	*	6.35	0.6	*
15	4	2	R5	8.65	-	0.63	264	*	8.95	1.4	*
16	4	2	R5	8.65	B	0.68	283	175	8.93	1.1	0.44
17	4	3	R5	8.65	-	0.99	206	73	13.32	3.2	3.28

VI. CONCLUSION AND FURTHER WORK

A literature survey in the field of machinery and robotics safety showed that limit values are often specified without any appropriate injury severity or without considering the variety of the human body with locations of totally different characteristics. In the robotics community there are promising approaches to specify limit values in consensus with specific consequences, which are considered as tolerable or critical. In our opinion none of these approaches are adequate enough since their limit values have not been verified with living humans or their corresponding consequences leading to inefficient operation conditions (slow and less useful robot velocities) or have no statistical relevance. To overcome all these lacks we have begun a comprehensive study with the goal to define an appropriate injury severity for pHRI from an occupational safety perspective. Through consultation with physicians and experts for occupational safety we propose that mild contusions including the appearance of an edema or a bruise should be the maximum injury severity for pHRI. We have presented how this threshold can be backed up with verified limit values, which in turn are obtained through experimental collision tests with live test subjects. The promising results gathered during the preliminary phase of the study turn out that our approach has great potential to contribute the current standardization efforts in pHRI.

Up to now, it is not clear which quantity has the most relevant influence on injuries due to blunt impacts. This is the primary objective of the following phase of our study in which we plan to examine more subjects at five locations by

[1] Stress result: PTL = pain tolerance level, B = bruise
[2] Trigger of the TekScan system failed

using three different masses and all available impactors. Furthermore, we intend to use high-end ultrasound scanner with better imaging capabilities to improve the examination of the stressed body locations.

APPENDIX

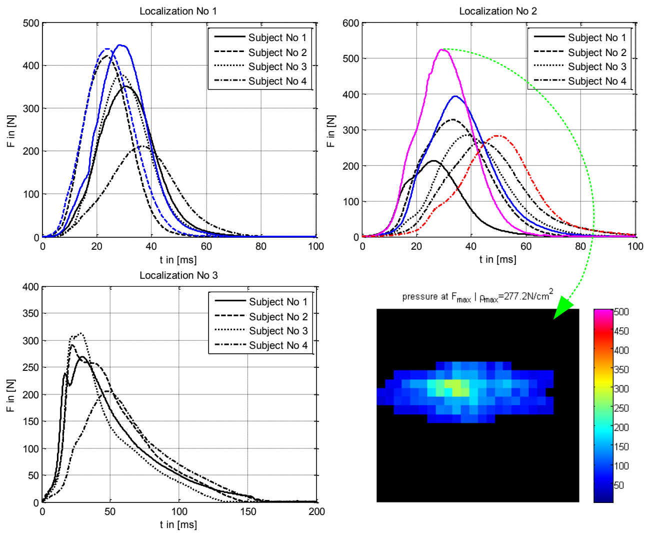

Figure 7. Results for all locations – blue: PTL reached, red: bruise occurred, pink: PTL reached and briuse occurred

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