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Robot-Dummy Crash Tests for Robot Safety Assessment

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Abstract— **New technologies and processes enhance the need for direct human-robot-interaction, to fully exploit the potential of robots' accuracy and humans' adaptability. Therefore, the hazardous potential of the involved robot manipulator needs to be minimised. Limits must be set, so that only an acceptable severity of injury for the human will remain in case of an unintended contact between the robot and a human. Current standardisation for industrial robot systems does not sufficiently address the subject of close human-robot-cooperation, thereby restricting the implementation of the newest technology. The aim of the reported research is to demonstrate the possibilities to assess the safety performance of robot systems by robot-dummy impact evaluation.**

In this paper, methods from the automotive industry are investigated on their transferability to the situation in robotics. Anthropomorphic test devices, so called crash test dummies, that resemble the human's kinematic response in car crashes are analysed during a robot-dummy impact. A simulation setup with the dummy FAT ES-2 representing the operator and an industrial robot is realised within LS-DYNA to conduct impacts of the robot arm against the head and the chest. The resulting Head Injury Index (HIC), the Viscous Criteria (VC) for the chest and the Pubic Symphysis Peak Force (PSPF) for the pelvis are discussed, showing their potential and limitations for the situation in robotics.

I. INTRODUCTION

To assure safety in human-robot-cooperation, the hazardous potential of the robot needs to be known. Only then it can be reduced to a minimum. Boundary values need to be defined for robotics, so that only an acceptable severity of injury can arise in case of a technical or human failure.

In chapter II the current situation in robotics is illustrated and the aim of the crash evaluation of robots with anthropomorphic test devices is further specified. Today's standardisation and regulation stays behind the possibilities of technological innovations in robotics. The insight arising from an intrinsic safety assessment of robot systems will establish a high potential for optimisation in the field of robot safety.

In chapter III crash test simulations with a robot and a dummy are conducted and analysed. With the SMART NS 16 model from Comau and the side impact dummy model FAT ES-2, representing the worker, scenarios for human-robot-cooperation are set up and evaluated on arising injury indices. Thereby the Head Injury Index (HIC), the Viscous Criteria (VC) and the Pubic Symphysis Peak Force (PSPF) are computed and analysed.

II. MOTIVATION AND TARGET

Since the market launch of the first robots in the mid sixties, the field of applications and the directions in the robot development have significantly changed. The market demand of industrial robots worldwide has increased about 25% in 2005, but the European market denotes a decline of 9%. Stagnation in the traditional application field, in the automotive industry, cuts down the demand while at the same time the proportion of robots in other branches such as in the food industry, in production of household articles and in woodworking and furniture treatment rises [8]. Besides new branches and processes new communication channels and operation modes are developed. Assistant systems that are designed for close human-robot-cooperation are getting more and more introduced into industry and even in the household. Thereby the strict enclosing of the robot with fences out of aluminium or steel has to be released. Only then one can benefit from the adaptability and decision-making ability of the human and the strength and precision of the robot at the same time to build up flexible and efficient systems for production and machining processes [14], [6].

Considerations on passive and active safety have to be more and more focused on the robot development. The robot behind the fence is no longer the sole solution to avoid the contact between the robot and the human, but the possible contact between the user and the robot is a pre-condition to fulfil tasks in robot-human-cooperation. This leads to the new requirement of guaranteeing a minimum hazard of the involved human at any time of the process.

A. State of the Art in Human-Robot-Cooperation

The European norm "DIN EN 775 Safety of manipulating robots" [5] which is right now revised and converted into the international standard "ISO 10218: Robots for industrial environments - Safety requirements" forms the current basis for safety in a robot cell. Already with the implementation of the DIN EN 775 the possible installation of a robot system within reach of a human was considered under highest security conditions. One of the targets of the ISO 10218 now is to further provide regulations for the robot-human-cooperation [10].

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Fig.1 describes the development of robot cells in industry. On the left the classical robot cell, as certified by the EN 775 is described, where the human and the robot are locally separated. In the setup in the middle the local separation is released, but a separation due to different time slots for the human and the robot is still given. With the appliance of the ISO 10218 robot cells as described in the right picture in Fig.1, where the human is present in the active workspace of the robot for a coexistent manipulation or operation of work pieces, can be certified.

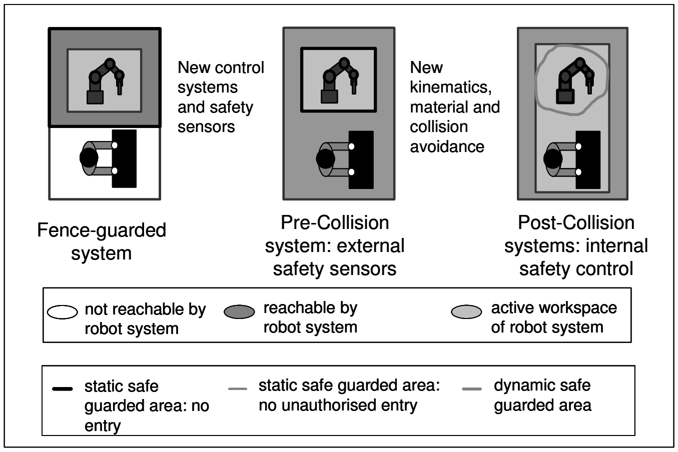

Fig. 1. From the Classical Robot Cell to close Human-Robot-Interaction

B. Objective

In the automotive industry the performance of an automobile during a crash test is taken as a sales promoting argument and thereby fosters the development of advanced safety systems. In robotics the procedure to use real accident data and simulations of collisions with crash test dummies to enhance the design and the functionality of robot systems has not been conducted so far. The work described in this paper deals with the question if the methods for crashworthiness assessment from the automotive industry can be applied to robotics. It will be investigated what kind of approaches and evaluation schemes can be transferred to robotics to assess and enhance the safety performance of robot systems. In chapter III robot-dummy scenarios are implemented into LS-DYNA [1] a Finite Element (FE) software explicitly designated for crashworthiness analyses. They are then investigated on arising injury indices during an unintended contact of the robot against the dummy.

The target of this study is to establish machine independent maximum permissible quantitative values, without neglecting the characteristics of the specific robot system. Compared to the current standardisation that defines maximum velocities for robot systems in the presence of a human independent from the involved kinematics, the specification of injury boundaries yields for machines with different hazardous potential to different requirements. The same safety requirement results in minor restrictions for the use of light structures and additionally secured robot systems. The use of light weight material and the development of parallel kinematics that apply smaller inertia at the tool centre point promise enhanced safety for human-robot-cooperation and allow higher maximum velocities for a system [2], [7].

III. ROBOT CRASH MODELLING IN LS-DYNA

For robotics detailed studies on accidents and thereby arising injuries hardly exist. One of the few accessible studies from Sweden is described in [3]. Even if the robot installations explored thereby did not allow any contact between the human and the robot, numerous and sometimes severe accidents happened due to the violation of safety mechanisms. One result of the studies is that head injuries do account for a high number of the occurred severe accidents. Especially the fact that most of the accidents could have been avoided if the operator would have regarded all safety devices confirms the need for clear regulations.

To establish the method of crash simulation as an efficient tool to optimise the design and to set up boundary values for human-robot-cooperation commercially available tools should be investigated on their potential and limitations. The explicit FE solver LS-DYNA has been selected for the analysis in this paper, where the time step is computed as a function of the smallest mesh size and the underlying material properties to assure convergence. LS-DYNA is explicitly designed for crash simulation and provides specific contact formulations for that purpose [11]. The CAD data of the robot is meshed and integrated into the FE code. Then a crash scenario with contact between the robot and the FE model of the side impact dummy FAT ES-2 (developed by the DYNAmore GmbH and partners in collaboration with the German Association for Automotive Research) is simulated and analysed.

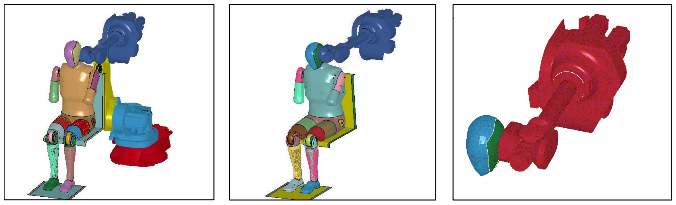

Fig. 2. Robot-Dummy Crash Simulation Setups

Injury values for different body regions will be evaluated corresponding to the procedure in the automotive industry. Therefore an impact of the robot against different body parts of the dummy will be simulated and accelerations, displacements and forces on the head, the chest and the pelvis of the dummy will be computed. The simulated scenario corresponds to a seated worker that is struck by a robot from the left side to which it can respond by freely drawing aside in the direction of the impact (see Fig.2 on

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[1] LS-DYNA by Livermore Software Technology Corporation: http://www.lsdyna.com/

TABLE I
MATERIAL CHARACTERISTICS OF COMAU NS SMART 16

Material	Rigid - MAT_020
Poisson μ	0.34
Density ρ $[\frac{kg}{m^3}]$	2 800.00
Elastictiy module E $[\frac{N}{mm^2}]$	72 600.0 0

the left). It is to mention that for the ongoing evaluation the full kinematical behaviour of the dummy during its motion can be neglected as only the first milliseconds after the impact are relevant for the computation of the injury indices here. Thus, the setup with a seated worker is no restriction for the investigation of human-robot-cooperation.

The robot is modeled as a rigid body with four node shell elements. The robot arm simulates an impactor that strikes the dummy non-braked with a constant velocity of $v = 5.0\frac{^\circ}{s}$ up to $v = 50.0\frac{^\circ}{s}$ around its first axis. To optimise the computing time, the geometrical model of the robot is reduced to its upper part (third to sixth axes) which is the part of the robot directly involved in the crash. Due to the huge discrepancy of the stiffness of the $200kg$ industrial robot to the $90kg$ elastic dummy model the dynamical behaviour of the robot due to its kinematic can be neglected for a first analysis (see Fig.2 centre). Thus, the whole robot arm can be regarded as one single rigid body. The technical specification of the implemented SMART NS 16 results in the material characteristics listed in Table I.

The contact definition between the robot and the dummy is realised via the surface/surface contact of the LS-DYNA code with a static and dynamic friction of $f = 0.3$ [11].

A. *Head Impact Simulation with Comau SMART NS 16 and ES-2 Dummy*

The head has been identified as the body part that is involved in a high number of accidents as well as the body part that accounts in many cases for severe injuries, as pointed out in biomechanical studies [9]. As these observations match with the experiences from the Swedish study on robotic accidents [3] the first crash analysis will be carried out for the impact of the robot against the dummy head.

To further reduce the computing effort, first simulations have been conducted to investigate the behaviour of the head kinematics against the stiffness of the rest of the dummy. Therefore the head of the ES-2 is detached from the rest of the dummy and the head is simulated with free motion to the neck (see Fig.2 on the right). Afterwards the results have been compared with the ones where the full model of the ES-2 had been included into the simulation.

In Fig.3 the acceleration of the dummy head during an impact of the robot with a rotational velocity of $20\frac{^\circ}{s}$ around the first robot axis is illustrated. It is computed via an accelerometer defined in the centre of gravity of the dummy head. With resulting track speeds of $0.093\frac{m}{s}$ up to $0.930\frac{m}{s}$ at the contact point of the robot a deviation of the maximum resultant head acceleration of about 5% can be observed, whereas form and length of the acceleration curve are nearly unaltered.

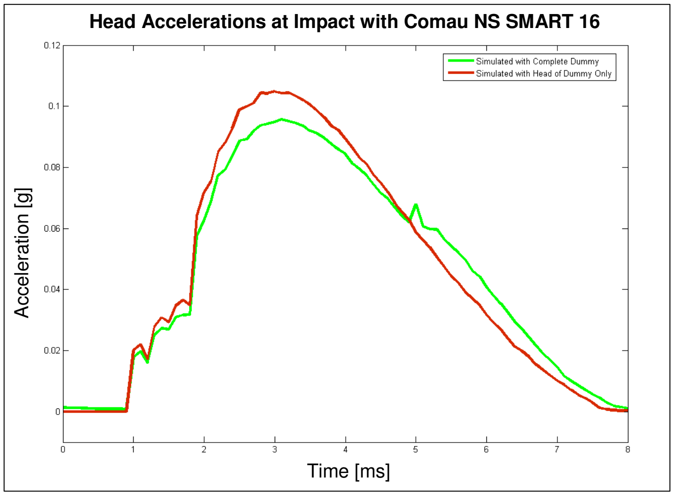

Fig. 3. Comparison of the Accelerations on the Dummy Head with Complete and Reduced Model of the ES-2 for Robot Rotational Motion at Speed $v = 20\frac{^\circ}{s}$

This results in sufficient accuracy for the aim of this investigation. The analysis is further supported by statements of other authors, that the kinemtical behaviour of the human head is independent from the neck stiffness for short time (here $\leq 10ms$) impacts of the human head (see [15], [1]).

The most famous injury index in literature, the HIC, is chosen for the interpretation of the results of the simulations [4]. The HIC is computed from the maximum of the norm of the integral of the linear acceleration of the head as in (1):

$$HIC = \max\left((t_2 - t_1)\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right)^{\frac{5}{2}}\right) , \quad (1)$$

with the corresponding time interval $I = [t_1, t_2]$ and the resultant linear head acceleration $a(t)$ in $[g]$ [4].

Fig.4 illustrates the output of the simulations with the above described reduced robot geometry and the reduced ES-2 model (see Fig.2 on the right). At the y-axis the resultant acceleration of the head that is initiated by the impact of the robot against the left side of the head is plotted against the time. Different constant velocities for the robot motion have been simulated. The acceleration rises steeply during the first $3ms$ after the impact until it reaches its maximum and then drops down again close to 0. At the lower velocities that lead to smaller accelerations a slower decay can be observed. The form of the acceleration curve is nearly independent from the velocity, but different forms, material and motion influence the curve form [12]. The pure variation of the velocity only results in the variation of the height of the maximum of the acceleration. Within this paper where only one robot model is evaluated, further results on the influence of the shape of the contact area are not taken into account, but will be investigated in further studies, as these results will then be able to give further hints for safe design in assitive robotics.

For the evaluation of the HIC, whose value is indicated in Fig.4 next to the underlying acceleration curve, (1) has been computed. In the literature it is differentiated for the evaluation of the HIC between the HIC15 and the HIC36, depending on the length of the impact interval (in milliseconds) [4]. Different boundary values for the assessment of the injury severity correspond to each interval length. The limitation of the interval should guarantee that no additional acceleration resulting from some backlash, distort the result arising from the main impact.

Fig.4 exhibits for the short stiff impact of the robot arm against the dummy head a significantly small impact interval of $5ms$ up to $10ms$. The HIC values computed in the presented simulations range far below the boundary limits for the HIC15 that are proposed in the automotive industry for severe injury. Hereby it has to be taken into account that the impact interval revealed for the robot-dummy impact are significantly smaller than the ones that result from a car-dummy-crash. The injury index limits derived from the automotive industry are specifically adapted to these crash scenarios, such as the specific amount of energies and loadings that are released during a car crash, which makes it difficult to interpret the quantitative result of the HIC. At short stiff impacts as in the robot-human crash the accelerations are possibly not the mechanical exposure that account for the heaviest damage of the head.

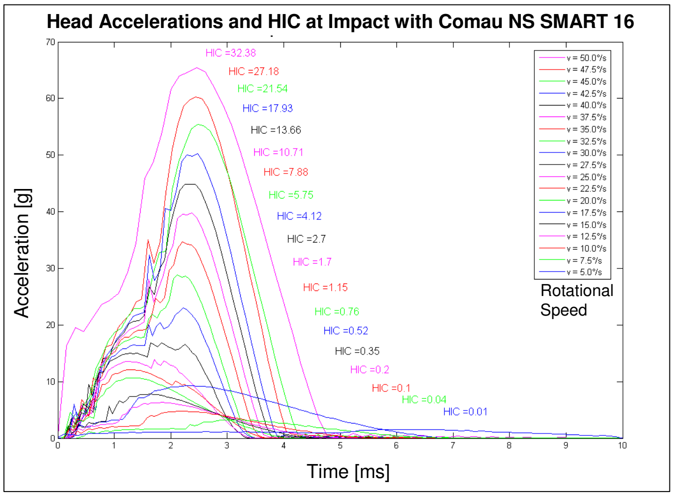

Fig. 4. Course of the Head Accelerations at the Impact of the SMART NS 16 against the ES-2 with Different Constant Speed $v = 0.093\frac{m}{s} - 0.930\frac{m}{s}$ at the Contact Point, with Corresponding HIC-Value

Thus, it can be stated that even if tools from crash evaluation in the automotive industry can be adapted, the interpretation of the resulting data cannot be adopted without specific adjustment to robotics. Further it has to be considered that the HIC is not only the most popular but also the most controversial of the injury indices. Its limited information value concerning possible occurring brain injury is often emphasised [9]. Before starting to set up boundary values for injury indices for robotics further biomechanical information on potential injuries due to short stiff impacts needs to be gathered. 3D head models such as the ULP model from the Université Louis-Pasteur Strasbourg, that are explicitly validated against experimental data from short stiff impacts, might be promising for further studies [15],[13].

B. *Chest Impact Simulation with Comau SMART NS 16 and ES-2 Dummy*

This section focuses on the evaluation of the Viscous Criteria (VC) as a further injury index which describes the effect of the impact on the chest [4]. The scenario described at the beginning of this chapter has been retained with the robot being repositioned so that the ES-2 is impacted at the middle rib (Fig.5). The model of the robot and its motions correspond to the ones described in section III-A.

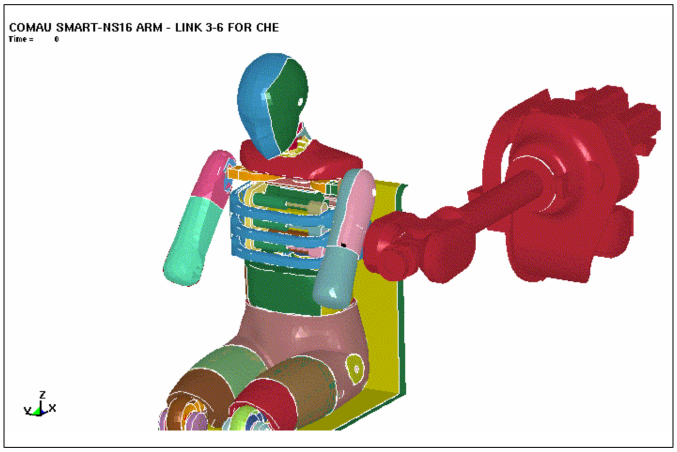

Fig. 5. LS-DYNA Simulation Setup for Chest Impact with SMART NS 16 and ES-2

The evaluation of the chest intrusion for the 3 single ribs of the ES-2 delivers a similar curve, with the lowest rib experiencing the highest intrusion. This can be explained by the fact that there is the least covering of the chest by the arm and due to the kinematics of the dummy the least possibility to bent over and escape the impact. As injury criteria the product of the relative compression $d(t)$ and the velocity of deformation of the rib $v(t)$ is computed like in (2), whose maximum defines the VC.

$$VC = \max\left(d(t) * v(t)\right) = \max\left(\frac{y(t)}{0.5 * b} * \frac{d[y(t)]}{dt}\right), \quad (2)$$

where b is a dummy specific constant, describing the depth of the dummy chest, here $b = 140mm$. The deformation $y(t)$ can be directly read out for each rib from the FE dummy model.

The motion profiles of the different velocities have been for comparability reasons chosen in that way that the robot arm proceeds with its motion for a path of $200mm$ after the first contact with the dummy before it stops. Fig.6 displays the relative intrusion of the lower rib of the ES-2 against the path of the robot. The right curve describes the VC-curve whose maximum is the VC value. The temporal development of the intrusion is not visible in Fig.6 but is accounted for in the computation of the VC. As for the head evaluation, the resulting VC-values ≤ 0.06 only resemble very small injury indices for the chest during the impact. The progress of the intrusion curve in Fig.6 on the left side reveals a stable behaviour of the dummy model over the simulated velocities. But still deeper knowledge on the behaviour of the human body during short impacts needs to be gained before the value of the VC can be interpreted.

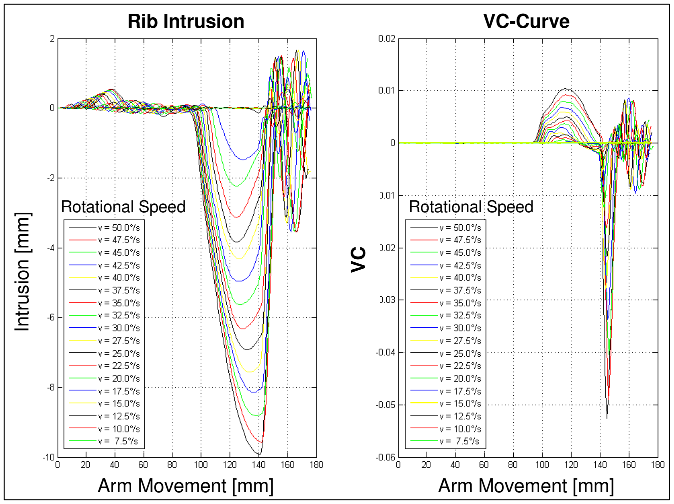

Fig. 6. Evaluation of the Rib Intrusion of the Lower Rib of the ES-2 with Different Constant Speed $v = 0.093\frac{m}{s}$ up to $0.930\frac{m}{s}$ at the Contact Point

C. Pelvis Impact Simulation with Comau SMART NS 16 and ES-2 Dummy

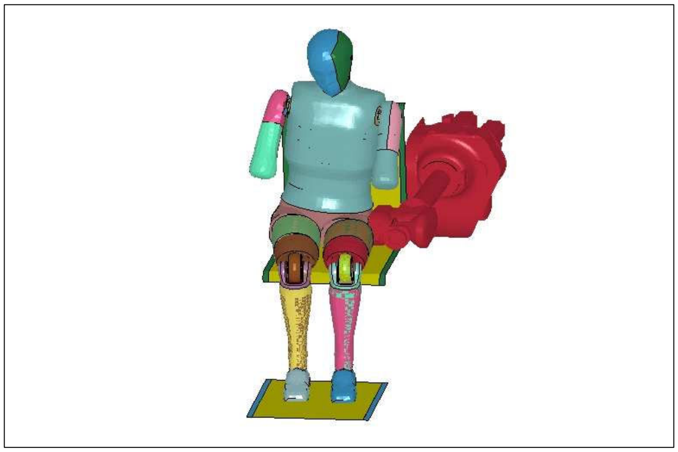

Fig. 7. Impact of NS SMART 16 at Lower Extremities

Further relocation of the robot within the setup for human-robot-cooperation leads to an impact scenario for the lower extremities of the dummy model. The constant robot motion from above is adapted with which the robot impacts the ES-2 on the pelvis, as can be seen in Fig.7.

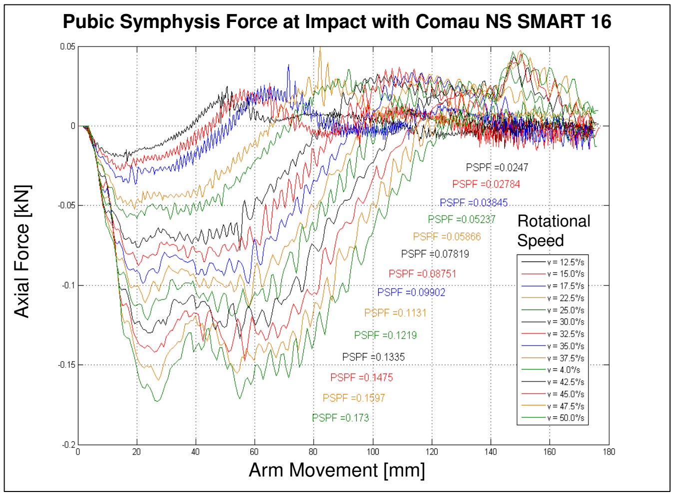

Fig. 8. Course of the Measured Pubic Symphysis Force of the ES-2 with Correspoding Peak at Different Constant Speed $v = 0.233\frac{m}{s}$ up to $0.930\frac{m}{s}$ at the Contact Point

For the impact against the pelvis of the dummy the forces that are applied to the pubic symphysis are evaluated and plotted against the path of the robot arm as described in section III-B. The results from the prior sections that reveal a stable behaviour of the dummy during the speed variation can be also observed for the lower extremities that are analysed hereby. The PSPF, which represents the absolute maximum of the arising axial force of the pubic symphysis, and its corresponding force course is shown within Fig.8.

IV. CONCLUSION AND OUTLOOK

The methods and tools from the automotive industry, where the safety performance of cars is rated with the help of anthropomorphic crash test dummies, provide a high potential for the transferability to robotics. In the robot-dummy crash simulations with the Comau SMART NS 16 and the FAT ES-2 in LS-DYNA conducted in this study, the FE model for head and chest impacts reveals a high robustness. The evaluation delivers coherent results for the head accelerations, the chest intrusion and the pubic symphysis force. But at the same time the computed injury indices show a large deviation to the injury indices obtained from standard car crashes.

Thus, the quantitative rating tablets from the automotive industry cannot be directly transferred to robotics. The assessment scheme for robotics has to be specifically designed for the characteristics stiffness and impact intervals arising in robot-human crash. Thereby it is unavoidable to consider further know-how from biomechanics concerning the capacity of the human body. The mechanical exposures to the human body that result in the most severe injuries in a robot-human crash differ from the ones in car crashes and is investigated with further simulations accompanied by experimental setups.

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