Approaching Asimov's 1st Law: The "Impact" of the Robot's Weight Class

Sami Haddadin, Alin Albu-Schäffer, Gerd Hirzinger
Institute of Robotics and Mechatronics
DLR - German Aerospace Center
P.O. Box 1116, D-82230 Wessling, Germany
{sami.haddadin, alin.albu-schaeffer, gerd.hirzinger}@dlr.de

***Abstract*— The desired coexistence of robotic systems and humans in the same physical domain, by sharing their workspace and actually cooperating in a physical manner, poses the very fundamental problem of ensuring safety to the user. In this paper we will show the influence of the robot mass and velocity during blunt unconstrained impacts with humans. Several robots with weights ranging from $15 - 2500$ kg at different impact velocities are going to be impacted with a mechanical human head mockup. This is used to measure the so-called Head Injury Criterion, mostly a measure for brain injury.**

Apart from injuries indicated by this criterion we point out that e.g. fractures of facial bones are actually very likely to occur during collisions at typical robot velocities. Therefore, this much more appropriate injury mechanism has to be evaluated more in detail.

Finally, we motivate the need to investigate possible injuries occurring if the human is clamped by determining the breaking distance of the investigated robots.

I. Motivation & Introduction

Bringing robots and humans spatially together leads to the fundamental concern of how to ensure safety to the human. As Asimov already noted very early, safety has priority if robots are close to humans [1]. During such unexpected collisions, various injury sources are present: e.g. fast blunt impacts, dynamic and quasistatic clamping, or being cut by sharp tools. Fundamental work on human-robot impacts under certain worst-case conditions and resulting injuries was carried out in [2], [3], [4], taking a look at a robot speed up to 2m/s. According to ISO-10218 [5], which defines new collaborative operation requirements for industrial robots, one of the following conditions always has to be fulfilled for allowing human-robot interaction: The TCP/flange velocity needs to be $\leq$ 0.25m/s, the maximum dynamic power $\leq$ 80W, or the maximum static force $\leq$ 150N. In our opinion these requirements tend to be quite restrictive and strongly limit the performance of the robot.

Further aspects concerning safety in human-robot interaction were evaluated in [6], [7], [8]. However, attempts to investigate real world threats via impact tests at standardized crash-test facilities and use the outcome to analyze safety issues during physical human-robot interaction were to our knowledge only carried out in [2]. In order to quantify the potential danger emanating from the DLR lightweight-robot (LWRIII), we conducted and evaluated impact tests at the Crash-Test Center of the German Automobile Club ADAC. The outcome of the dummy crash-tests indicated a very low injury risk with respect to evaluated injury criteria posed by rigid impacts with the LWRIII. These results presented in [2], [9] indicate that a robot, even with arbitrary mass driving not much faster than 2m/s is not able to become dangerous to a non-clamped human head with respect to typical Severity Indices. These are injury indicators used in the automobile industry which usually focus on head acceleration. The most prominent measure in literature is the Head Injury Criterion (HIC) [10], defined as

$$\mathrm{HIC}_{36} = \max_{\Delta t} \left\{ \Delta t \left(\frac{1}{\Delta t} \int_{t_1}^{t_2} ||\ddot{\mathbf{x}}_H||_2 \mathrm{d}t \right)^{\left(\frac{5}{2}\right)} \right\} \leq 650 \qquad (1)$$
$$\Delta t = t_2 - t_1 \leq \Delta t_{\max} = 36\mathrm{ms}.$$

$||\ddot{\mathbf{x}}_H||$ is the resulting acceleration of the human head[1] and has to be measured in $\mathrm{g} = 9.81\mathrm{m/s}^2$. Since the numerical value of a Severity Index as the HIC itself is not a direct measure of injury severity, there exist mappings from Severity Index to injury level and/or probability of injury level. The injury level is usually expressed by the so-called AIS-level [11]. The Abbreviated Injury Scale (AIS) is an internationally established definition of injury severity and classifies it from 0 (none) to 6 (fatal). For further information on HIC, AIS and other Severity Indices (not only for the head, but also for the neck and chest), please refer to [2].

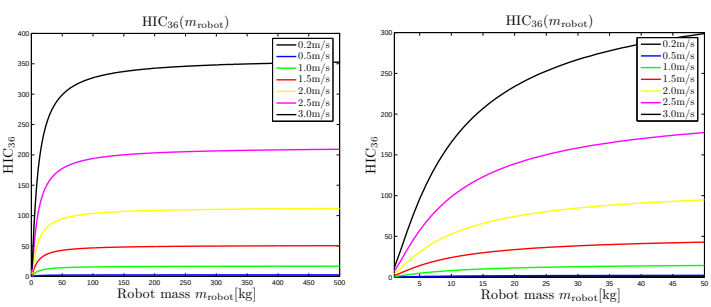

Fig. 1. Resulting Head Injury Criterion calculated from simulated 1DOF impacts between a robot with increasing mass and a dummy head model extracted from real impact data.

In Fig.1 simulated results for the HIC resulting from a robot colliding with a dummy head model are outlined. The Head Injury Criterion was evaluated for robot masses up to 500kg and graphs were obtained for impact velocities of $||\mathbf{x}_R|| \in$

[1] $||\ddot{\mathbf{x}}||_2$ =Euclidean norm

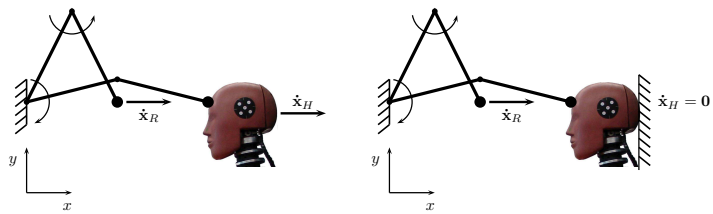

Fig. 2. Two types of blunt impacts: Without (left) and with clamping (right).

$\{0.2, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0\}$m/s. They show that the HIC saturates for increasing robot mass at each impact velocity. This on the other hand indicates that at some point increasing robot mass does not result in higher HIC.

Consequently, no robot whatever mass it has could become life-threatening at 2m/s by means of **impact** related criteria used in the automobile industry, as long as clamping and impacts with sharp surfaces can be excluded.

Generally, there are two major types of blunt impacts: impacts with and without clamping (see Fig.2). In this paper we will present non-constrained impact tests verifying the above mentioned theoretical extrapolation and at the same time show that impact force is a possible and more appropriate severity index, since it indicates the fracture of facial and cranial bones which is very likely to occur at typical robot speeds. In the end we briefly show that clamping is a very important mechanism which has up to now not attracted much attention but is definitely worth to be evaluated more in detail. In Sec.II the general setup, inlcuding the evaluated robots is described. Sec.III presents the results and evaluation of the impact tests and finally in Sec.IV a conclusion and outlook will be carried out.

II. Test Setup

A. The Dummy Head

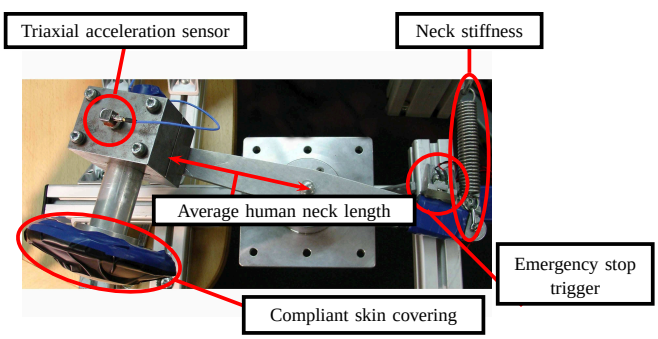

Fig. 3. Dummy-dummy harmonized with the HIII dummy (see Fig.4).

In [2] results and implications from impact tests at certified crash-test facilities of the German Automobile Club ADAC

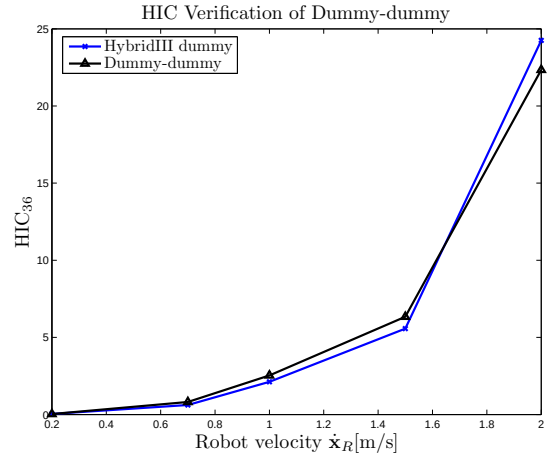

Fig. 4. Verification of the Dummy-dummy by comparing resulting HIC values obtained by real HIII dummy crash-tests with the LWRIII.

were carried out with the LWRIII (see Fig.5a). Because such crashtests are very expensive[2], we decided to use the resulting outcome of these impact tests to built up a simplified setup that mimics a Hybrid III (HIII) dummy head and use it for the evaluation of other robots. In Fig.3 this test-bed, consisting of a dummy head-neck complex, equipped with a triaxial acceleration sensor, is shown.

In Fig.4 the HIC values obtained by the impact tests at the ADAC, i.e. with a real HIII dummy and the ones we measured with the simplified Dummy-dummy are compared. It shows that our setup is capable of reproducing very similar numerical values and therefore serves from now on as a basis for comparing different robots with respect to the Head Injury Criterion.

B. Evaluated Robots

In order to cover a wide range of robots and be able to verify the saturation effect explained in [2], we compare the LWRIII with the KUKA KR3-SI, the KUKA KR6 and the KUKA KR500. In Fig.5 the setup for each robot is shown, whereas the same impactor was mounted on each robot. All industrial robots were rotating about the first axis and evaluated for the same Cartesian velocity at the Tool Center Point (TCP) as the LWRIII in [2]. The reflected Cartesian inertia in impact direction for the evaluated configurations is given in Tab.I along with a very short comparison on the robot key facts. A feature of the KR3-SI which has to be mentioned is the safeguarding of the tool by means of an intermediate flange with breakaway function. This triggers the emergency stop in case the contact force at the TCP exceeds a certain threshold. In combination with the mounted impactor its weight is 1.4kg.

[2]For an entire test series with different robots at various impact velocities this would be a very high expense.

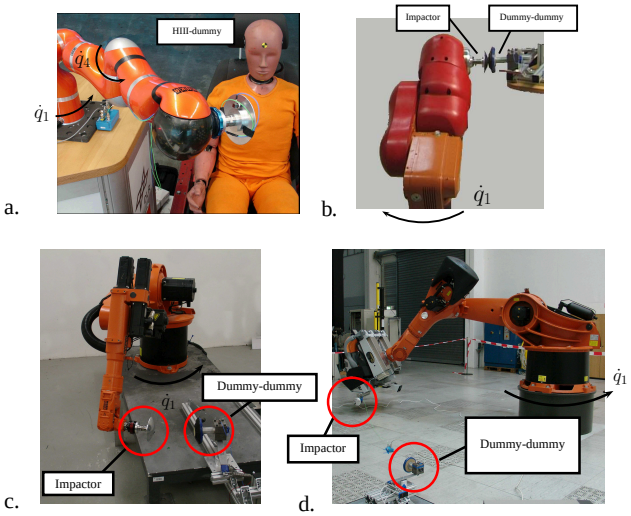

Fig. 5. Setup of impact tests with the LWRIII, KUKA KR3-SI, KUKA KR6 and KUKA KR500.

Robot	Weight [kg]	Nom. Load [kg]	Refl. Inertia [kg]
LWRIII	14	14	4
Kuka KR3-SI	54	3	12
Kuka KR6	235	6	67
Kuka KR500	2350	500	1870

TABLE I

KEY FACTS OF EVALUATED ROBOTS.

III. RESULTS

A. Head Injury Criterion

In Fig.6 the resulting HIC values for the different robots are visualized for $||\dot{\mathbf{x}}_R|| \in \{0.7\ 1.0\ 1.5\ 2.0\}\mathrm{m/s}$ and are additionally classified with respect to the EuroNCAP[3]. The values for the KR3-SI are even lower than for the LWRIII because the intermediate flange decouples the impactor during the moment of impact from the entire robot. Therefore, only the flange-impactor complex is involved in the impact. Clearly, the saturation effect explained in Sec.I was observed, as the numerical values for the KR6 or KR500 do not significantly differ. Thus, the simulation results presented in Fig.1 should be considered as conservative and that the actual saturation value is even noticeably lower than predicted. The results indicate a **very low** potential injury occurring during such impacts with respect to the HIC and rated according to the EuroNCAP [12]. The probability of a resulting injury level of AIS ≥ 3

[3]The initial crash-tests with the LWRIII were carried out at the ADAC. They are the basis for the tests presented in this paper and are evaluated according to the EuroNCAP. This is a manufacturer independent crash-test program, based on the AIS. For further information on these issues please refer to [2].

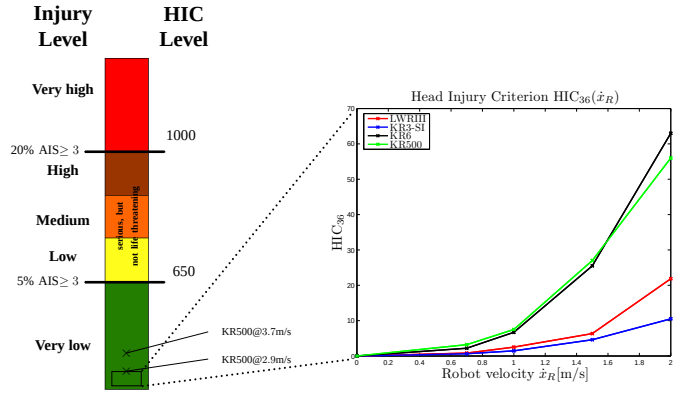

Fig. 6. Resulting HIC_{36} values for varying impact velocities and for all robots, rated according to the EuroNCAP *Assessment Protocol And Biomechanical Limits*.

obtained by the extended Prasad/Mertz curves[4] is for all robots maximally $\approx 0.15\%$, i.e. negligible. The HIC for the KR500 measured at 80% and 100% maximum joint velocity $\dot{q}_1^{\max}$, coresponding to a Cartesian velocity of 2.9 and $3.7\mathrm{m/s}$, was 135 and 246. This means that even such an enormous robot as the KR500 cannot pose a significant threat by means of impact to the human head measured by typical Severity Indices from automobile crash-testing. The injury levels for these values are located in the *green* area and the probability of AIS ≥ 3-injuries are 1.2% and 3.6% for the faster impacts with the KR500 (see Fig.6).

B. Head Impact Forces

As shown in Sec.III-A the HIC values for all robots, even for the KR500 at maximum joint velocity in outstretched configuration, are far lower than *low*[5]. Therefore, other less severe injury mechanisms possibly occurring during human-robot collisions like fractions of cranial & facial bones have to be investigated. This particular injury is motivated by recorded contact forces of the impacts which were in the order of the fracture tolerance of these bones (see Tab.II). Contact forces were analyzed during the robot-HIII/Dummy-dummy impacts for all four robots and show an interesting behaviour (Fig.7.a-d). Generally, one can see the decreasing impact duration with growing robot speed for all robots. Furthermore, contact forces increase faster with impact velocity, the heavier the robot is. At the same time a saturation effect similar to the one of HIC can be observed. The maximum impact force at $2\mathrm{m/s}$ for the KR6 and KR500 exceeds the force produced by the LWRIII only by $0.5\mathrm{kN}$. According to [14] the HIII head has similar impact characteristics to the human frontal area[6] which gives

[4]For a detailed evaluation please refer to [2].

[5]With cadaver impacts it is shown as well that the head would not be ripped of the body during a very fast impact at 20km/h [13]. However, the actual injury of the neck during such a collision is still under investigation.

[6]However, this is the only area of a HIII head having similar contact properties as the human. Other areas show considerably higher stiffness than its human equivalents and thus cannot be used as a comparison basis.

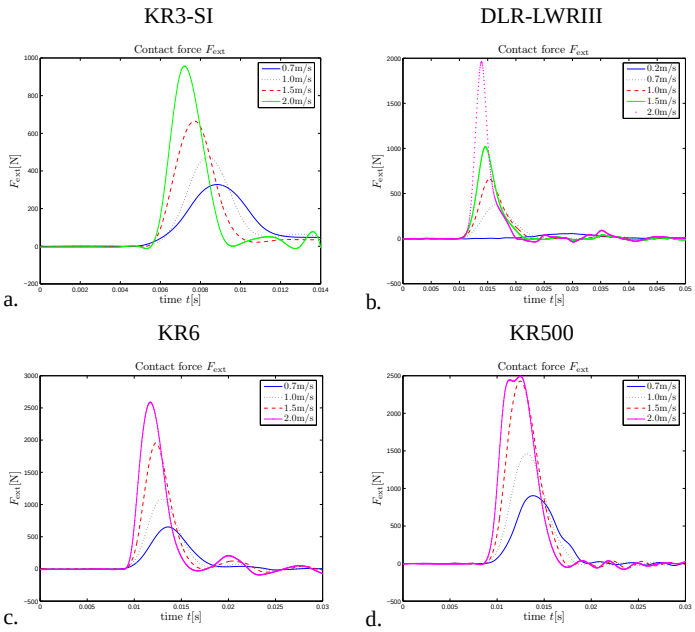

Fig. 7. Measured contact/impact forces of the KUKA KR3-SI, LWRIII, KUKA KR6 and KUKA KR500 colliding with the Dummy-dummy at various impact velocities.

the opportunity to use our real impact measurements to analyze the possibility of fractures of the frontal bones (see Fig.8).

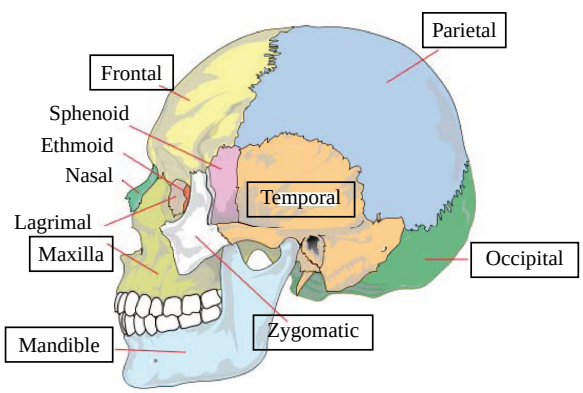

Fig. 8. (Simplified) anatomy of the human skull [15].

1) Fraction Forces: In Tab.II limits of the facial and cranial bones according to [16], [17] are listed. The corresponding terminology of the head anatomy is illustrated in Fig.8. Generally, the fracture force highly depends on the contact area used for such tests. Fractures are categorized into linear, depressed and depressed with punch through fractures. For this kind of injury there does not exist a mapping to AIS. This is because according to [18] fractures as isolated injuries are usually all classified as AIS $= 1$ (superficial injury). Self-explanatory this does not apply to possible consequential damages as punch throughs which unquestionably could become extremely dangerous (e.g. causing brain injuries).

Facial bone	FRACTURE FORCE
Mandible (A-P)	1.78kN
Mandible (lateral)	0.89kN
Maxilla	0.66kN
Zygoma	0.89kN
Cranial bone	**FRACTURE FORCE**
Frontal	4.0kN
Temporo-Parietal	3.12kN
Occiput	6.41kN

TABLE II
FACIAL IMPACT TOLERANCE OF CADAVER HEADS.

2) Evaluating Real Impact Forces for the Head: As shown in Tab.II the fracture force of the frontal bone is 4kN, i.e. it is almost twice as high as the maximum measured forces of 2.5kN (at velocities up to 2m/s). As mentioned above, only the frontal bone can be evaluated by HIII (or Dummy-dummy) impact tests and since the measured impact forces do not reach critical values for the frontal bone, we carried out impact simulations to judge whether other cranial or facial bones are at risk.

3) Head Model: In order to carry out impact simulations, suitable models of the area of interest are needed: Depending on the contact area we will utilize models obtained by human cadaver tests carried out in [19], [20], [14], [21]. Models of the bones mainly differ in terms of stiffness and their particular fracture force (see Tab.II).

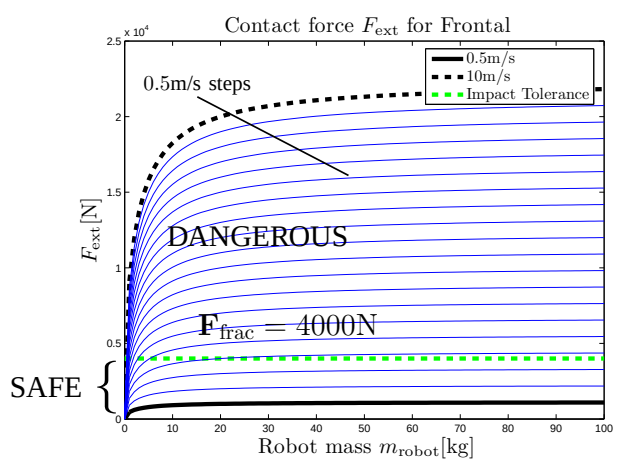

Fig. 9. Contact forces for simulated impacts between a robot and the frontal area showing the dependency on the robot mass and velocity. The impact velocity steps are 0.5m/s. The stiffness of the frontal bone is $\approx 10^6 \frac{\text{N}}{\text{m}}$.

4) Facial Impact simulation: In Fig.9,10 the dependency of the impact force with respect to the robot mass and velocity (the robot is assumed to move with constant velocity) for the

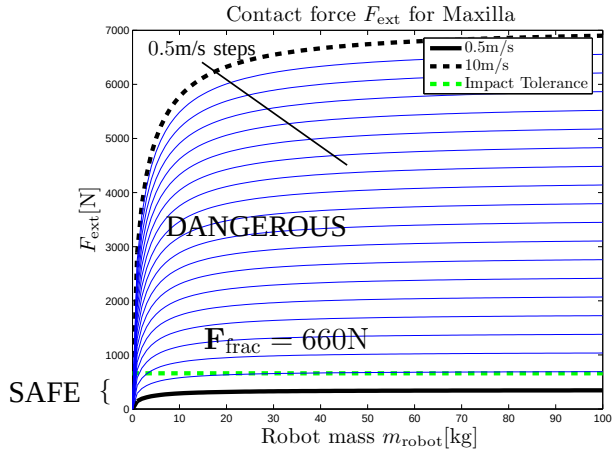

Fig. 10. Contact forces for simulated impacts between a robot and the maxilla showing the dependency on the robot mass and velocity. The impact velocity steps are 0.5m/s. The stiffness of the maxilla is $\approx 10^5 \frac{\text{N}}{\text{m}}$.

frontal bone and the maxilla are visualized. For all bones[7] except the frontal one it seems that starting from the saturation mass value[8], a velocity between $0.5 - 1.0\text{m/s}$ is enough to cause fractions. The frontal bone is the most resistant one, generally withstanding impacts approximately up to 2m/s. Furthermore, it becomes clear that especially for robots with less than 5kg reflected inertia at the moment of impact the velocity can be significantly higher without exceeding the limit contact force. For weaker bones like the maxilla impact speeds of 2m/s are already posing a major fracture source even for low-inertia robots.

C. Soccer Kick

Fig. 11. Impact tests with a football and a KUKA KR500.

[7]Simulations for other facial and cranial bones were carried out as well. They show similar behaviour.

[8]The robot mass from which on a further increase does not result in significantly higher forces.

In order to show by a very intuitive experiment that a non-constrained impact cannot be life threatening, a soccer ball was kicked with the KUKA KR500 at maximum joint velocity (see Fig.11 and especially the corresponding video at www.robotic.dlr.de/safe-robot). The ball hits the ground after a flight of only $\approx$ 2m. In comparison, a human performed a kick as well and one can clearly see how slow and careful he hits the ball in order not to shoot farther. Additionally, a rather hard shot was taken to show the dramatic contrast to the robot. This example clearly gives a better feeling what it means to be hit by the robot at such a velocities.

D. Clamping

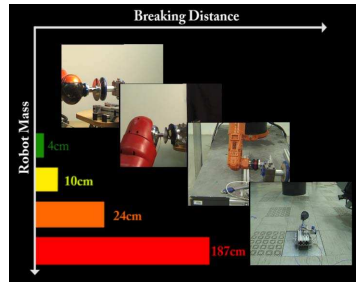

Fig. 12. Comparing the breaking distance of robots with different weights.

After this impact analysis leading to the conclusion that no robot is able to cause life-threatening injury by means of HIC we want to motivate the important but up to now only marginally mentioned, injury mechanisms induced by a constrained impact. What happens if the impacted body part is clamped during an impact? Of course this analysis makes only sense if the robot has the ability to detect a collision and stops because otherwise an industrial robot is unquestionably able to exert forces high enough to crush any human body part and even kill a human[9]. To get a feeling of the major influence of robot mass, the breaking distances of the robots were compared to each other. Of course, the robot would be additionally decelerated in the presence of a human, but still, the breaking distance already shows how dangerous clamping becomes at increasing robot mass. In order to stop the LWRIII we used the disturbance observer introduced in [22] and the collision reaction consisted of setting $\boldsymbol{\theta}_d = \boldsymbol{\theta}$, where $\boldsymbol{\theta}_d$ is the desired configuration and $\boldsymbol{\theta}$ is the motor position. This causes the robot to stop. For the industrial robots an electrical contactor (see Fig.3), which directly triggered a trajectory-preserving breaking was used[10].

The enclosed video clearly shows that increasing the robot mass results in very large breaking distances up to 690mm for the KR500 at robot speed of 2m/s. At maximum joint velocity the KR500 needs almost 2m for a full stop (see

[9]At this point one has to distinguish between impact and crushing forces.

[10]Emergency stop categroy 1 according to DIN EN 60204 for the KR6 and KR500. This means fastest possible stop without breaks, i.e. controlled. Currently, tests with breaks are conducted and evaluated as well. However, the breaking tests with the KR3 already used its breaks.

Fig.12). Further simulations we carried out, based on these real measurements, indicated that already the KR3 can potentially cause quite severe injuries due to its weight. The KR6 is already heavy enough to cause injury which is classified as **very high** with respect to the EuroNCAP [11].

IV. Conclusion & Outlook

We proved via experiment the statement given in [2] that potential injury of the head, occurring during an impact, will saturate with increasing robot mass and is from a certain robot mass on only depending on the impact velocity. Thus, typical Severity Indices focusing just on the moment of impact like the Head Injury Criterion are not an appropriate measure of injury severity in robotics because no robot exceeds their safety critical thresholds. This is due to the usually significantly lower velocities of the robots compared to impact tests carried out in automobile crash-testing. Summarized blunt head impacts without clamping at moderate robot speed are, no matter how massive the robot is, definitely not life-threatening[12]. This statement was supported by the soccer ball kick carried out with the KUKA KR500, showing that the speed of the robot is the major factor defining possible injury level.

To our knowledge these measurement represent the first of this kind carried out for various different robots, ranging from manipulators especially designed for physical human-robot interaction to various types of industrial robots with increasing weight.

However, other less dangerous injuries, as fractures of facial and cranial bones, are very likely to occur already at moderate velocities and seem to be a more relevant injury mechanism for investigation.

Although the actual impact cannot **severely** injure a human there are other threats still to be investigated. Here, we pointed out the immanent risk posed by the robots weight and the resulting breaking distance if the human is clamped. Although the robots were triggered by the electrical contactor, one is not able to extract the kinetic energy out of the robot fast enough to stop in tolerable distance.

Videos illustrating and supporting key aspects of the paper are available for download at www.robotic.dlr.de/safe-robot.

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[11] Currently, we work on quantifying the effect of the robot mass and velocity in case of clamping. Here we will concentrate on a pure motivation and problem description. A paper discussing many open issues is currently in preparation.

[12] The presented evaluation is carried out for average males and not for females or children.

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