Evaluation of Collision Detection and Reaction for a Human-Friendly Robot on Biological Tissues

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***Abstract*— Up to now, mostly blunt human-robot impacts were investigated in the robotics literature. In this context, the influence of robot mass and velocity during rigid impacts with and without the possibility of the human being clamped was quantified. In this paper an analysis of soft-tissue injuries caused by sharp tools which are mounted on/grasped by a robot and an evaluation of possible countermeasures are carried out as the next step down the road to full safety for robots in physical Human-Robot Interaction. To our knowledge for the first time in robotics, we present various experimental results with biological tissues showing the high performance of our collision detection and reaction schemes even for contacts with sharp tools.**

I. Motivation & State of the Art

Industrial robots played up to now the most important role in real-world applications, while advanced highly sensorized robots have been usually kept in lab environments and remained in a prototypical stadium. Various factors such as low functional robustness, limited reliability, and lack in computing power have been hurdles in realizing robotic systems for highly demanding tasks in domestic environments or as robotic co-workers. The recent progress in technology maturity finally made it possible to realize systems with high levels of integration and large sensorial capabilities that are crossing this barrier and merging humans and robots in the same living spaces to a certain extent. In addition, the increasing efforts that various companies have invested to realize or at least to be able to plan the launch of first commercial service robotic products make it necessary to properly treat the fundamental question of how to ensure safety in human-robot coexistence. The immediate connection to the three (and later four) Laws of Robotics of the famous science fiction writer Isaac Asimov [1] becomes naturally apparent.

Although several countermeasures, criteria and control schemes for safe physical Human-Robot Interaction have been proposed in the literature [2], [3], [4], [5], [6], [7], [8], [9], [10], the main objective of actually quantifying and evaluating them on a biomechanical basis was only marginally addressed. First evaluations were carried out in [11], where the human pain tolerance[1] was estimated on the basis of human experiments. In [12], [13] further attempts in this direction were mainly carried out in simulation, while more recently an exhaustive evaluation of blunt impacts with various human body parts was performed in [14], [15], [16]. Earlier work presented in [17] focused on a more abstract injury classification.

In the context of soft-tissue injury, the basic question of what is the resulting injury for a human during undesired contact has not yet been analyzed exhaustively. Especially for the human biomechanics, injury severity and tolerance were hardly considered or only discussed on a qualitative basis. The work presented in [18], [19] shifted, for the first time in robotics, the focus to soft-tissue injuries. In [18], the first full attempt of a classification and synopsis of possible injuries in human-robot interaction was given, pointing out the need of investigating also soft-tissue injuries. The influence of different parameters and properties of the robot and the environment on the resulting injury severity was discussed and various injury indices were proposed, e.g., contact force or energy density. In [19], as previously in [17] and [7], skin stress was used as an index for assessing soft-tissue injuries, and an analysis was carried out showing the usefulness of stress as a reliable indicator.

The main contribution of this paper is to review our sensorless collision detection method and evaluate their efficiency in one of the most critical scenarios: impacts with sharp tools. We will treat stab/puncture wounds and incised wounds[2] and prove the effectiveness of our collision detection and reaction schemes for the DLR-Lightweight Robot (DLR-LWRIII).

II. Collision Detection & Reaction

A. Collision Detection

The collision detection scheme used in the framework of this paper is the disturbance observer introduced in [3], [4], see Fig. 1. In the upper part the rigid body dynamics is sketched (while neglecting the joint damping), whereas the lower part represents the actual observer. This can also be interpreted as a Hamiltonian observer, since its basic concept is to observe the angular momentum $\mathbf{p} = \mathbf{M}(\mathbf{q})\dot{\mathbf{q}}$, as proposed in [20] and [8]. It can be shown that the output $\hat{\mathbf{r}}$ of the disturbance observer is a component-wise decoupled and filtered version of the joint

[1] In this work the Somatic Pain was considered as a suitable criterion for determining a safety limit against mechanical stimuli.

[2] In general, stab/puncture wounds are potentially more lethal. However, for very sensitive zones, deep cuts can be equally dangerous.

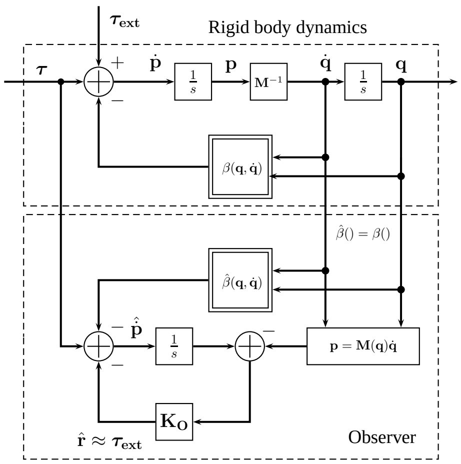

Fig. 1. Block diagram of the disturbance observer, estimating a 1st order filtered version $\hat{\mathbf{r}}$ of the external torque $\boldsymbol{\tau}_{\mathbf{ext}}$. The nonlinear feedback term $\beta(\mathbf{q},\dot{\mathbf{q}})$ is defined as $\beta(\mathbf{q},\dot{\mathbf{q}}) := \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) - \dot{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}}$.

torque $\boldsymbol{\tau}_{\mathbf{ext}}$ resulting from external collision

$$\hat{r}^i = \frac{1}{sT_O^i + 1}\tau_{\text{ext}}^i = \frac{K_O^i}{s + K_O^i}\tau_{\text{ext}}^i \approx \tau_{\text{ext}}^i, \quad \forall i \in \{1, ..., n\}, \tag{1}$$

where the filter constants $T_O^i = 1/K_O^i$ of the ith external joint torque signal are related to the observer gains K_O^i. Furthermore, all components of $\hat{\mathbf{r}} = [\hat{r}_1 \dots \hat{r}_n]^T$ are used to generate a collision detection signal as

$$CD = \begin{cases} 1 & \text{if } \exists i: \ |\hat{r}^i| > \hat{r}_{\text{det}}^i \\ 0 & \text{else,} \end{cases} \tag{2}$$

where $\hat{r}_{\text{det}}^i > 0$ is the collision threshold for the ith axis.

B. Collision Reaction

After a collision has been detected and isolated, an appropriate robot reaction has to be triggered. Various reaction strategies were proposed in [4], [3] and three of them are tested and compared in this paper for soft-tissue contact (swine) with sharp tools. One of our goals is to be able to evaluate the effectivity of the robot collision handling in a critical scenario. As will be shown, the collision detection and reaction strategies can make the difference between serious, even lethal injuries and no injury at all. The investigated collision strategies are

Strategy 0: This is the baseline for comparison. The robot shows no reaction at all, i.e., continues to follow the reference trajectory $\boldsymbol{\theta_d}$(t), where $\boldsymbol{\theta_d}$ is the desired motor position (as computed from the desired link position $\boldsymbol{q_d}$ in case of joint elasticity).

Strategy 1: Stop the robot as soon as a collision is detected, meaning to set $\boldsymbol{\theta_d}(\text{t}) = \boldsymbol{\theta_c}$ for $t \geq t_c$, where $\boldsymbol{\theta_c}$ is the motor position at the time t_c of collision detection.

Strategy 2: Switch from position control to zero-gravity torque control [21], [22] and let the robot react in a very convenient compliant manner.

In previous papers [15], [16] we focused on blunt impacts. However, one of the most critical situations is an impact with sharp tools, such as knifes, scissors, or scalpels. By common sense, we would expect that no robot reaction would be able to prevent serious injury in this case. The performed experiments show instead a more differentiated picture and very encouraging results.

III. Experiments

In this section various experiments will be presented which help analyzing the injury severity possibly occurring if a robot with a sharp tool penetrates a soft material. Especially the dynamics of such an impact is worth to be investigated since during rigid (unconstrained) collisions presented in [14] the dynamics is so fast that a robot is not able to reduce the impact characteristics by the collision detection and reaction [14], [15], [16]. However, a subjective safe feeling could definitely be experienced by the users. Despite this limitation in reactivity for blunt impacts, our results showed that countermeasures are not absolutely crucial in that case since rigid impacts pose only a very limited risk at typical robot velocities. This is definitely not the case for soft-tissue injuries caused by a stab, since the injury severity due to the penetration can reach a lethal level[3]. Because of the much lower dynamics compared to rigid impacts, the requirements on a reactive robot concerning detection and reaction speed are somewhat relaxed. At a fist glance it seems surprising that it is not possible to counterbalance rigid blunt robot-human impacts, which are definitely not life-threatening, while very dangerous or even lethal contacts with sharp tools on soft tissues seem handable to a certain extent. One purpose of the present experiments is to prove this statement. In this paper we will consider moving the robot under position control with or without collision detection and utilizing joint torque sensing. The contact force is measured with a JR3 Force-Torque sensor at the final flange[4].

A. Investigated Tools

The variety of tools one could consider countless and therefore only a set of representative tools was selected, see Fig. 2. We focussed on sharp tools to analyze the problem of stabbing, but we chose different blade profiles and lengths to study also cutting which turned out to be a large injury threat.

B. Silicone Block

As a first experimental contact material, a silicone block[5] was used in order to get a feeling for the sensitivity and effectiveness of the collision detection and reaction in soft contact, see Fig. 3 (left). Due to its standardized properties it can be used as a benchmark material (in contrast to some biological

[3]Of course the worst-case depends on the exact location of the underlying potentially injured organs.

[4]Please note that this sensor is **only** used for measurement and **not** for collision detection.

[5]The used silicone was *Silastic T2* with a Shore hardness of A40 and manufacture by *Dow Corning*.

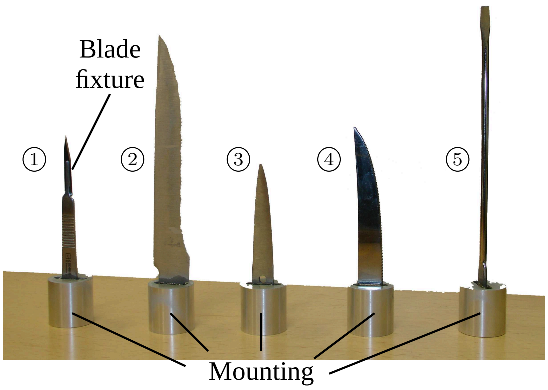

Fig. 2. Investigated tools: ① scalpel, ② kitchen knife, ③ scissors, ④ steak knife, ⑤ screwdriver. These were selected as potentially very dangerous tools one could think of in domestic/service applications of robots. All tools were removed from their original fixtures and glued into new mountings. A fixed connection between tool and robot was guaranteed so as not to have compliance which would reduce the transferred forces.

tissue). These tests were conducted at a Cartesian velocity of 0.25 m/s. Fig. 3 (right) shows how effective the collision detection and reaction can help to reduce contact forces and the penetration depth. The desired goal configuration was located at a depth of 8 cm in the silicone block. Without any collision reaction strategy the penetration was 35 mm at a contact force of 220 N, with joint 6 exceeding its maximum torque[6]. With activated collision detection and reaction the maximum penetration depth was substantially reduced to ≤ 6 mm at a contact force of 40 N, i.e., a reduction by a factor of ≈ 5.

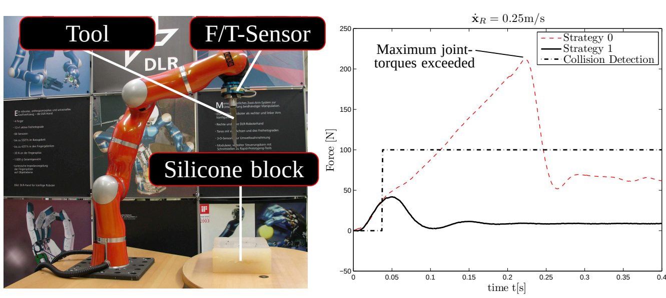

Fig. 3. Stabbing tests with the silicone block and the kitchen knife mounted on the robot.

C. Swine Experiments

In order to obtain results with real biological tissues we conducted experiments with a swine leg[7], see Fig. 4. There are indeed differences compared to humans and also due to the changing properties of tissues post mortem, but we still believe that conducting experiments with such a natural tissue is of great importance and value. To our understanding, these investigations could be fundamental to robotic safety. Of course, classical impact experiments with knifes in forensic medicine, as described, e.g., in [23], [24], did not take any robot behavior into account which in turn vastly influences the resulting injury.

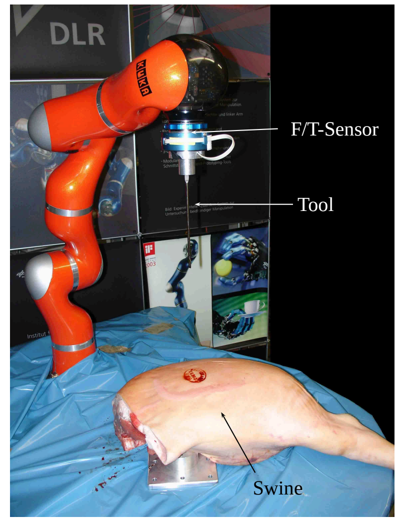

Fig. 4. Setup for the swine series of tests. The DLR Lightweight Robot III is equipped with a sharp tool and a JR3. The F/T sensor is used here just to measure the contact forces for analysis. The collision detection is based only on motor encoder and joint torque sensing (i.e., **not** on the JR3).

1) Stabbing: It is clear that stabbing is likely to lead to a lethal situation and the fatality of this type of injuries needs very careful evaluation. However, our experiments indicated very encouraging results on the safety-preserving capabilities of the robot when used in combination with the aforementioned collision detection method and reaction strategies.

Table I and Fig. 5 summarize the outcome of the stabbing tests. The trajectory of the robot was chosen such that it moves on a straight vertical line (see also Fig. 8) contacting the skin in normal direction with the tool axis and having the desired goal configuration located approximately 16 cm in the swine. The investigated robot velocities were 0.16 m/s and 0.64 m/s. With the screwdriver mounted, the robot was not able to penetrate the swine skin at all. For this tool the maximum nominal joint torques were always exceeded and a low-level safety mechanism engaged the brakes of the robot. For the other tools Table I gives the measured values for the maximum penetration depth d_p, the penetration time t_p, i.e., the interval between initial contact and first occurance of skin penetration (which can be interpreted as the *available reaction time* to prevent skin injury), the penetration force F_p at t_p and finally the elastic deflection x_p before penetration, i.e. the deflection of the skin which has to be reached with a particular tool for penetration.

As shown in Tab. I without collision detection (Strategy 0) all sharp tools penetrate into the tissue with their entire blade length (except for the very long kitchen knife). However, at low speed a very good chance of detection and reaction exists and especially for the kitchen knife and the scissors a full injury prevention seems possible. For the steak knife the success depends on the contact location and ranges from no

[6]This causes a low-level safety feature to stop the robot immediately by engaging its brakes.

[7]From an anatomical point of view swines are commonly accepted as being very similar to human beings. Impact experiments in automobile crash-testing or in forensic medicine use results on swines as first test or even as reliable prediction of outcome on human tissues.

		$\dot{\mathbf{x}}_R = 0.16$ m/s				$\dot{\mathbf{x}}_R = 0.64$ m/s			
Tool	Strategy	d_P [mm]	t_P [ms]	F_P [N]	x_P [mm]	d_P [mm]	t_P [ms]	F_P [N]	x_P [mm]
Steak knife	0	full	100	15	14	full	14	11	10
	1	none/4	–	–	–	22	14	11	10
	2	$3-5$	100	15	14	64	14	11	10
Scissors	0	full	195	60	25	full	47	65	29
	1	none	–	–	–	18	34	45	21
	2	none	–	–	–	42	42	65	25
Kitchen knife	0	98	240	76	29	135	55	73	32
	1	none	–	–	–	1	48	60	29
	2	none	–	–	–	18	55	76	31
Scalpel	0	full	50	5	8	full	15	5	10
	1	17	50	5	8	17	15	5	10
	2	17	50	5	8	39	15	5	10

TABLE I
RESULTS OF THE STABBING EXPERIMENTS.

penetration up to a penetration depth of a few millimeters. For the scalpel there is actually no real chance to detect the penetration of the blade. The collision detection is only triggered by the fixture of the blade which has a significantly larger cross section (see Fig. 2).

For larger velocities a significant observation can be made. Switching from Strategy 1 to Strategy 2 causes a higher penetration depth of the latter due of to its passive behavior. Because the robot behaves in this control mode as a free floating mass with a certain amount of initial kinetic energy: Therefore, the tissue is further penetrated until the robot's energy is fully dissipated. On the other hand, Strategy 1 is able to limit the penetration depth to values which are lethal only in absolute worst-case scenarios, i.e. below 2.5 cm. The penetration force seems not to be velocity dependent.

Apart from the characteristic values of Tab. I the force profiles of the stabbing experiments are visualized in Fig. 5. ① shows the obtained graphs for the screwdriver, ② for the steak knife, ③ for the scissors, ④, for the kitchen knife, and ⑤ for the scalpel. The force-time evolution is plotted for all three strategies. When inspecting the plots the following can be observed:

- the instant of penetration is characterized by a significant force discontinuity (drop);
- a very low resistance is found after the instant in which the tool penetrates the subcutaneous tissue;
- force reduction by Strategy 2 is significantly slower compared to Strategy 1;
- after the initial penetration the contact force increases very slowly compared to the elastic force of the skin;

The influence of the tool mounting can be observed for Strategy 0, resulting in a dramatic increase in force. In case of the scalpel the quite different course needs to be explained. The very low penetration threshold is followed by an almost constant phase which represents the intrusion of the entire blade. For impact velocity 0.16 m/s the increase in force is caused by the fixture of the blade which therefore allows detection. For impact velocity 0.64 m/s the force increase due to the fixture is followed by a second one due to the mounting as for the other tools.

2) Cutting: The second injury mechanism which is investigated in this paper is cutting. The pure cut trajectory with a fixed object can be described by the desired constant tool orientation ϕ_1, the constant angle ϕ_2 of the cut direction, and the cutting velocity, see Fig. 6. Once ϕ_1 has been chosen the swine position is uniquely determined since the cut shall be carried out with the full available blade length. In our case $\phi_1 = 30^o$ was chosen. Investigated tools were the steak knife, the scalpel, and the kitchen knife. The question about which cutting angle ϕ_2 could lead to the worst case was answered experimentally ($\phi_2 = 10^o$).

During the experiments it became clear that cutting velocities must be quite high to cause damage to the skin and the underlying tissue. At low velocities up to 0.25 m/s no injury was observed and merely a scratch was found. However, at 0.8 m/s this changed dramatically (see Fig. 7): large and deep lacerations were caused by all tools if no safety feature was activated. The risk of such large and potentially lethal injuries was reduced by collision detection and reaction to an almost neglectable level at which penetration due to cuts took no longer place.

D. The most convincing argument

Since the presented experiments showed really promising results and proved how reliably one is able to promptly detect and react to collisions, some measurements are shown, where a human holds his arm in **free** space[8] against the moving robot holding a knife, see Fig. 8. The robot velocity in the vertical direction was progressively increased, having $\dot{\mathbf{x}}_R \in$

[8] A full evaluation for the case of free stabbing swines still has to be carried out but it will be definitely less dangerous compared to the constrained stabbing presented in this paper.

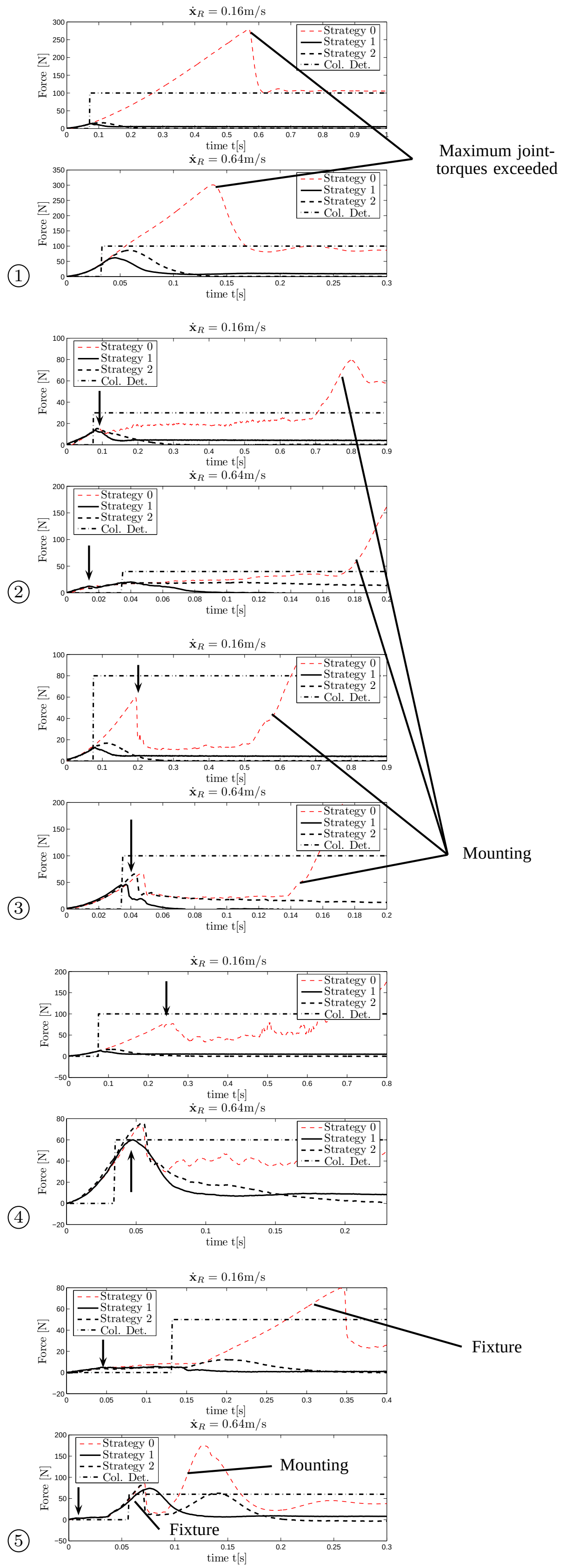

Fig. 5. Results of stabbing tests. ①: screwdriver, ②: steak knife, ③: scissors, ④: kitchen knife, ⑤: scalpel. The arrows denote the moment of penetration.

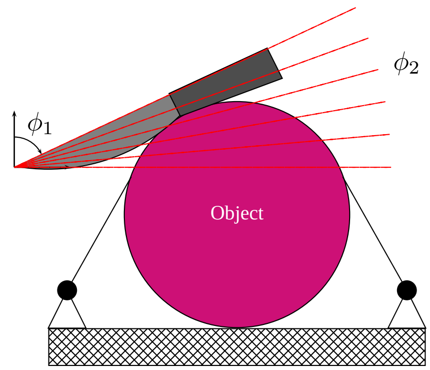

Fig. 6. Cutting trajectories for a fixed subject. ϕ_1 is the tool orientation and ϕ_2 the cutting direction. The tool is positioned such that the blade origin contacts the subject.

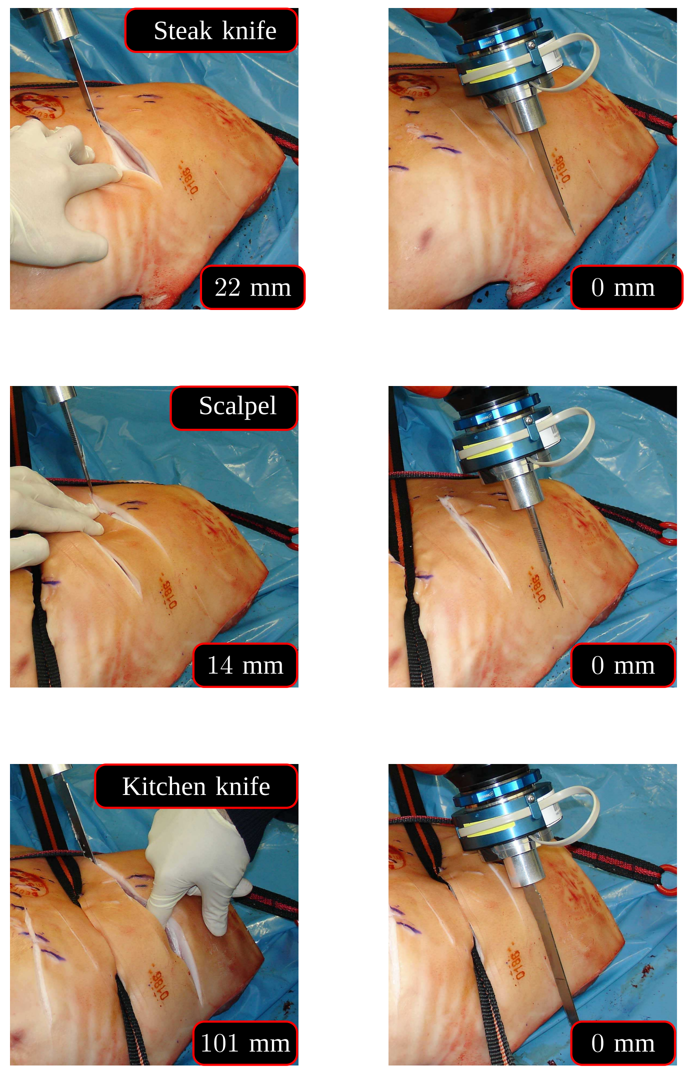

Fig. 7. Resulting injury due to cutting. On the left column the caused lacerations and their depth are indicated. All tools easily penetrated the tissue and cutting depths of up to 101 mm are reached. On the right column the effect of reacting to a collision is apparent. The robot stops as soon as a collision was detected (Strategy 1). No cut could be observed.

$\{0.1 \;\; 0.25 \;\; 0.5 \;\; 0.75\}$ m/s at the end-effector. In Fig. 9 the measured force during the collision with the human is plotted. Due to the collision detection the robot is able to prevent the human from being injured at all. The contact force was limited in this experiment to 7 N for 0.1 m/s, to 13 N at 0.25 m/s, to 23 N at 0.5 m/s and to 55 N at 0.75 m/s. Only for the largest evaluated velocity of 0.75 m/s a minimal scratch in the highest layer of the skin could be observed.

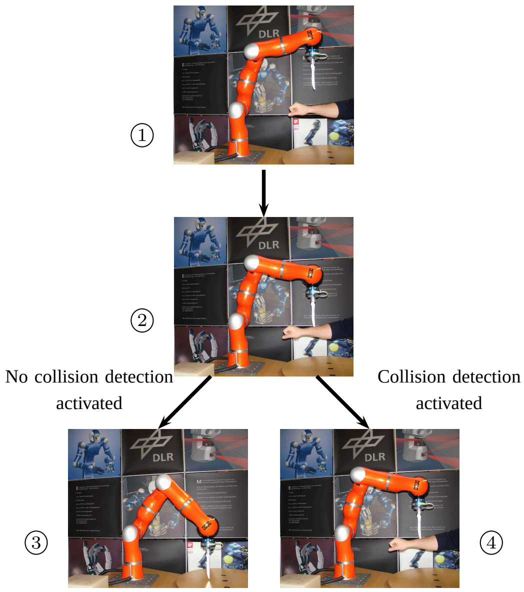

Fig. 8. Effectiveness of the collision detection and reaction. The human arm is hit by the robot at $\dot{\mathbf{x}}_R \in \{0.1 \;\; 0.25 \;\; 0.5 \;\; 0.75\}$ m/s. The desired trajectory of the robot is a straight line in vertical direction. ①: Initial robot configuration. ②: The robot moves along its desired trajectory ③: Desired goal configuration of the robot ④: The robot detects the collision with the human arm and stops before hurting the human.

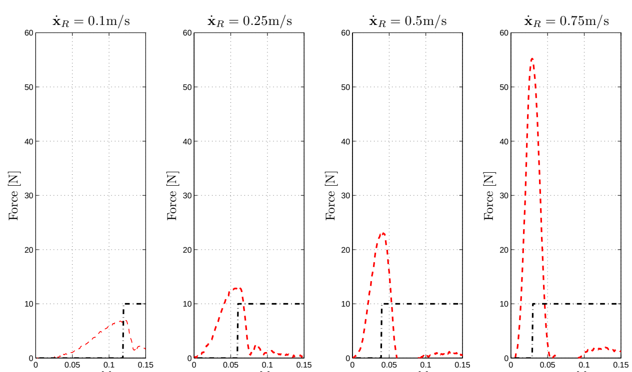

Fig. 9. Stabbing tests in free space with human volunteer. The force can be limited to subcritical values. The dashed line is the measured contact force and the dashed-dotted line is the collision detection signal.

IV. Conclusion & Outlook

An experimental evaluation of soft-tissue injuries in robotics and a verification of possible countermeasures by means of control were carried out. The treatment of such injuries is to our understanding fundamental and a crucial precondition to allow robots the handling of sharp tools in the presence of humans. In this paper we treated especially stab/puncture wounds caused by knifes. The fact that a knife can penetrate into deeper human inner regions and therefore threaten sensitive organs mainly motivated this evaluation. We tested various increasingly sharp tools ranging from a screwdriver to a scalpel and showed at the same time the huge benefit of the collision detection and reaction. In future work other usually non-lethal injuries as abrasions and contusions will be treated as well. Further experiments will focus on a detailed investigation of the effect of joint stiffness on improving safety.

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