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Soft-Tissue Injury in Robotics

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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 is carried out as the next step down the road to a full safety analysis of robots for HRI. We conducted an analysis of soft-tissue injuries based on available biomechanical and forensic data and to our knowledge for the first time in robotics present various experimental results with biological tissue for validation. Furthermore, possible countermeasures are evaluated quantitatively based biomechanically relevant quantities.**

I. MOTIVATION AND STATE OF THE ART

Currently, increasing effort is taken to understand injury mechanisms during physical human-robot interaction. Up to now only blunt impacts were treated to some exhaustive level in the literature [1], [2], [3], [4], leaving open the question of what can happen if a robot with an attached sharp tool can impact with a human. Naturally, the reservation against robots handling with sharp tools in human environments is enormously high. Till a robot will actually fulfill complex "helper" tasks in domestic environments, using sharp tools, massive safety investigation is still necessary. An important class of injuries to be analyzed in this context are soft-tissue injuries of which typical ones are depicted in Fig. 1. They range from usually less dangerous injuries as contusions or abrasions to very painful lacerations and even life threatening ones as stab/puncture wounds. Stab/puncture wounds are usually potentially more lethal than laceration. However, for very sensitive zones, as e.g. around the area of the underlying arteria carotis, deep cuts can be equally dangerous.

Although several countermeasures, criteria and control schemes for safe physical Human-Robot Interaction were proposed [5], [6], [7], [8], [9], the main objective of actually quantifying and evaluating them on a biomechanical basis was marginally addressed. Up to now the fundamental question of what is the resulting injury of a human during undesired contact was not discussed and analyzed in depth in the context of soft-tissue injury. Especially the human biomechanics, his injury tolerance and occurring injury severity were basically not considered or usually only discussed on a qualitative basis. Previous work conducted in [10] and [7] already introduced and analyzed skin stress as an injury index for assessing soft-tissue injury. Nevertheless, a real focus shift to the mentioned soft-tissue injuries was to our knowledge not carried out until [11] and [12].

Generally, soft tissue injury analysis in robotics was mainly model based so far. Knowing from own experience how uncertain and contestable simple models (and their parameterization) for such complex biomechanical processes are, we decided to treat this topic very empirically and acquire real data for injury thresholds. We think that these experiments provide reliable facts and can constitute a help for further evaluation and validation of models.

This paper has following main contributions:

1) Evaluate soft-tissue injuries caused by various possibly dangerous tools. We treat stab/puncture wounds and incised wounds.
2) Prove the effectiveness of our collision detection and reaction schemes for the DLR-Lightweight Robot III (LWRIII) with soft-tissue and volunteer tests. These countermeasures give us the possibility to drastically reduce the injury potential during stabbing and preventing even the slightest cutaneous injury during cutting.
3) Provide empirically relevant limit values for injury prevention for the case of sharp contact.

The paper is organized as follows. In Sec. II soft-tissue injuries caused by sharp tools are described. Sec. III briefly presents the used collision detection and reaction and discusses a simulation use-case. In Sec. IV various stabbing and cutting experiments are conducted using as test material silicone, pig tissue, and human volunteer tests for situations, which prove to be not critical by previous experiments[1].

II. SOFT-TISSUE INJURY CAUSED BY SHARP TOOLS

Fig. 1. Typical soft-tissue injuries: ①: Contusion (bruises, crushes, hematoma), ②: Stab/puncture wounds, ③: Abrasion, ④: Laceration (incised wounds/cuts, gashes, contused wounds).

In this section an overview of soft-tissue injury biomechanics that is useful in the context of this paper is given.

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[1] Please note this paper extends the preliminary results given in [13].

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A. Biomechanics of Soft-tissue Injury

Sharp contact can cause various characteristic injuries in the context of robotics. The most important ones are abrasions, contusions, lacerations, incised wounds, and puncture wounds.

- Abrasions or excoriations are the ablation of parts or the entire epidermis from the corium.
- Contusions are basically bleedings into tissue, which can be found in the skin, muscles and inner organs.
- A laceration can be described as a tear in the tissue and an incised wound is a transection in skin continuity, which is wider than deep.
- A puncture or stab/puncture wound on the other hand is usually characterized by being deeper than wide.

In this paper we focus on stab/puncture wounds and incised wounds/cuts in order to capture the vast threat posed by sharp tools as knifes, scalpels or scissors and leave the low severity injuries for future research.

In this paper the influence of underlying bones will be neglected and the evaluation focusses on areas as the abdomen or thigh. This can be considered as a worst-case since the underlying soft-tissue is very sensitive and a bone would (apart from the case of slipping of or impinging) reduce the possible injury severity. If e.g. an object hits the human thorax above the heart location and penetrates further it is possible to hit a heart protecting rib. In case the object does not slip or impinge nor is able to exert forces that are able to cause rib fracture, the possible injury is limited to the tissue till the rib and further rib injury. This is of course much less dangerous than if the robot tip penetrated between two ribs and reached the cardiac tissue. The analysis of this situation is left for future work.

Stab/puncture wounds were investigated in the forensic literature with different knifes and it was concluded that strain is not an appropriate measure to define a tolerance value for knifes and similar tools because the contact area is too small [14], [15], [16]. Instead, the evaluation of the penetration force F_p is proposed, which in our opinion is appropriate to be used in the context of robotics as well. Tolerance forces depend on the layers of clothing and range according to [15] from mean values of $F_p^1 = 76$ N for uncovered skin to $F_p^2 = 173$ N for three layers of typical clothing. Furthermore, the tolerance force correlates to a skin deflection x_p at, which the actual penetration takes place. This deflection is $x_p^1 = 1.24 \pm 0.49$ cm for naked skin and $x_p^2 = 2.26 \ \pm 0.61$ cm for multilayered clothes[2]. In this paper we assume the relationship to be linear in first approximation, meaning that the skin can be modeled during stabbing by a stiffness before penetration and a tolerance force, determining the moment of penetration, see Fig. 7. What happens after the knife actually penetrates is to our knowledge still not well investigated and needs further treatment and evaluation. First hints given in [16] show that a second significantly lower resistance after the initial skin penetration can be observed. As a first indicator we considered in our experiments the intrusion/penetration depth d_p to be a relevant quantity (of course depending on the location the skin is actually penetrated and the corresponding underlying tissue) to evaluate the severity of injury.

According to [18] no similar investigation of incised wounds/cuts was carried out up to now. This is presumably due to non existing forensic necessity. In this sense our analysis brings new insights into the understanding of this injury mechanism in a broader sense and not only for robotics.

After this introduction of necessary biomechanical/forensic definitions the used collision detection and reaction methods shall be briefly overviewed. Furthermore, their use as a countermeasure to soft-tissue injury caused by sharp tools is motivated by a simulation since initially it seemed not very realistic to be able to prevent e.g. injuries caused by knifes and scalpes. In this paper we use our detection and reaction strategies [5], [19] as a tool for a biomechanical evaluation of possible soft-tissue injuries with and without collision detection.

III. COLLISION DETECTION & REACTION

Countermeasures against soft-tissue injury can be manifold but a crucial feature has to be an effective physical collision detection and reaction. If an interaction force is detected the differentiation whether the robot is currently fulfilling a desired task as preparing food or constitutes a potential threat is still to be done. From our point of view this is a question of higher-level planning and human motion detection involving external sensing as e.g. a vision system. However, this separate topic is not within the scope of this paper.

In well designed industrial environments, distinguishing whether the occurring collision is part of an assembly task or a collision with the human could e.g. simply be solved by switching the collision detection off as soon as clamping of the human can be excluded due to the fact that the distance between the tool and the known environment (table) is lower than a threshold. In this situation a very good world model is necessary, which could be available in an industrial scenario.

Generally, as soon as a collision is identified as such, various reaction schemes can be thought of. In case of mounted sharp tools this reaction scheme needs to be treated very carefully, since e.g. activating the strategy of a free-floating compliant robot is still a dangerous threat with a mounted (or grasped) knife (of course a reduced one compared to a robot moving in position control).

A. The DLR Lightweight Robot III

In our evaluation we conducted simulations and experiments with the LWRIII, see Fig. 6. The LWRIII is a 7DOF lightweight robot with 1.1 m reach, moderately flexible joints (due to the use of harmonic drives and joint torque sensors), and was explicitely developed for the direct physical interaction and cooperation with humans. Its total weight as well as its nominal payload are 14 kg. Furthermore, it is equipped with joint torque sensors in each joint, enabling a direct interaction along the entire robotic structure. For details concerning the full design of the robot, please refer to [20] and [21].

Compared to the soft-tissue properties of the human during the investigated collisions throughout this paper the robot is very stiff. Thus, thresholds of penetration forces and other properties obtained by our measurements are not valid only

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[2] This evaluation was carried out at low velocities, therefore determining the static stab force. However, in [16] dynamic tests were conducted, which produced similar numerical values. In [17] stab tests with three different knifes led on the other hand to significantly lower penetration values.

for this particular robot but can directly be applied to other robots.

B. Collision Detection

The collision detection used in this work[3] was introduced and analyzed in [5], [19]. Its basic concept is to observe the generalized momentum $\mathbf{p} = \mathbf{M}(\mathbf{q})\dot{\mathbf{q}}$, as proposed in [22] and [23], with $\mathbf{M} \in \Re^{n\times n}$ being the manipulator mass matrix and $\mathbf{q}, \dot{\mathbf{q}} \in \Re^n$ the link position and velocity. It can be shown that the observed disturbance is a component-wise filtered version of the real external torque $\boldsymbol{\tau}_{\mathbf{ext}} \in \Re^n$. The collision threshold for each axis, which is mainly cased by sensor noise and model uncertainties was chosen to be $0.03\boldsymbol{\tau}_{\mathbf{max}}$, i.e. 3% of the maximum nominal torque $\boldsymbol{\tau}_{\mathbf{max}} \in \Re^n$ of the robot. This value already indicates that very low contact forces can be detected.

C. Collision Reaction

After a collision is detected and isolated an appropriate reaction has to be triggered. Therefore, various strategies were proposed in [5], [24] and three of them are tested and compared in this paper for soft-tissue contact (silicone, pig) with sharp tools. One goal is to be able to evaluate the effectiveness of the detection in a critical scenario. As is be shown in Sec. IV the collision detection can make the difference between serious, even lethal injuries and no injury at all. The investigated collision strategies in this paper are

Strategy 0: Keep the reference movement, i.e. show no reaction at all and continue to follow $\boldsymbol{\theta_d}$, where $\boldsymbol{\theta_d} \in \Re^n$ is the desired motor position. This is the reference behaviors.

Strategy 1: Stop the robot as soon as a collision is detected, meaning to set $\boldsymbol{\theta_d} = \boldsymbol{\theta}(t_c)$, where $\boldsymbol{\theta} \in \Re^n$ is the motor position and t_c is the instant of collision detection.

Strategy 2: Switch from position control to zero-gravity torque control [25], [26] and let the robot react in a very convenient compliant manner.

Before presenting the experiments a simulation use-case is discussed in the following, which was our initial motivation for evaluating our collision detection and reaction for a robot that moves such dangerous tools.

D. A Simulation Use-case with the LWRIII

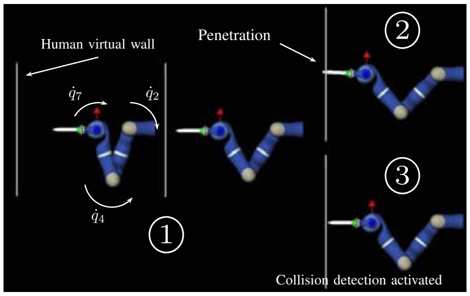

Fig. 2. Stabbing simulation with the full dynamic (flexible-joint robot) model of the LWRIII equipped with a knife.

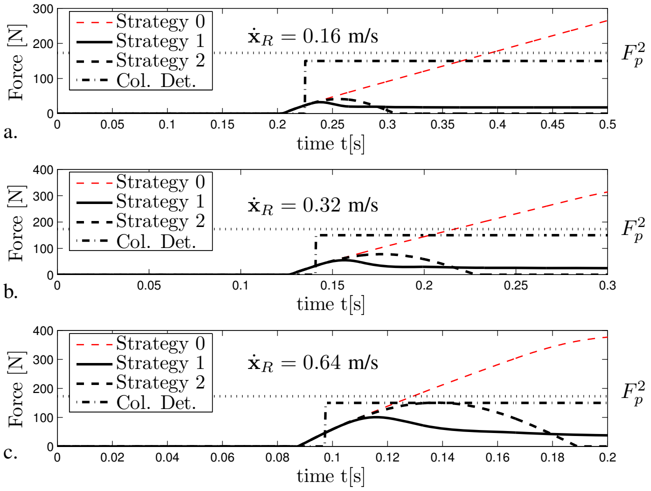

Fig. 3. Contact force in a stabbing simulation with the full dynamic model of the LWRIII equipped with a knife.

In this use-case the penetration of the human skin with a knife and its prevention is treated. A simple and reasonable contact model[4] for stabbing is available as mentioned in Sec. II. This simulation shows how easy it is to penetrate the human skin even with a robot moving at moderate speeds. Penetrating the human skin itself seems to be only a marginal injury but at the same time various vital organs as the heart or the liver are located relatively close under the body surface.

In order to quantify potentially lethal stabs we conducted ultrasonic measurements with ten human subjects to estimate the distance from the skin surface to the surface of the human heart[5]. Between the 4th or 5th intercostellar spaces the depth is measurable since the heart abuts on the thorax wall. Numerical values of $d_{\text{heart}} = 2.2$ cm to 2.7 cm were measured with a mean of $\bar{d}_{\text{heart}} = 2.4$ cm. This small distance points out how vulnerable human organs are as soon as penetration occurs. d_{heart} is an example of a meaningful value. Therefore, we propose to use the penetration depth as a severity index in robotics. This could be used as a maximum braking distance for a robot handling dangerous tools, therefore imposing also velocity limits for such tasks.

In Figure 2 the simulated trajectory of the robot with fixed base is depicted. The fully covered human stands 0.3 m before the stretched out singularity of the robot, see Fig. 2. The maximum joint velocity of the robot is 120^o/s and the desired motion is a straight line with reconfiguration from “elbow up” to “elbow down”. The maximum Cartesian velocity resulting from the maximum joint velocity in the 4th joint, whereas the 2nd and the 7th joint drive at half the velocity, is 0.64 m/s. In this simulation the Cartesian impact velocity was chosen to be $\dot{\mathbf{x}}_R \in \{0.16\ 0.32\ 0.64\}$ m/s for fully covered skin. We assume the human to have three layers of clothing. ① denotes the initial configuration of the robot. ② shows the clear penetration without any collision detection, and ③ exemplifies how the human skin can be protected by reacting e.g. with Strategy 1. This particular trajectory is not the worst-case but it corresponds to a typical robot configuration. In Fig. 3 the results of the simulation are

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[3] In our previous work we developed the collision detection scheme based on the internal joint torque sensors of the robot. This makes it possible to eliminate an additional 6DoF wrist sensor for sensing external forces/loads.

[4] The human soft-tissue is modeled as a virtual wall with the already mentioned spring constant and is assumed to be clamped, i.e. a worst-case scenario is treated..

[5] Currently, we evaluate the depth of other vital organs as the liver or the arteria carotis.

shown. Clearly, the effectiveness is apparent even for high Cartesian velocities. The skin is not penetrated since the robot is able to react sensitive and fast enough to prevent the human from being hurt. Furthermore, the properties of the collision reaction strategies become apparent: Since Strategy 1 actively stops the robot it reduces the contact force significantly faster than Strategy 2, which reacts delayed. This is due to the passive behavior of the robot in torque controlled mode with gravitation compensation. However, Strategy 2 is able to fully loose external contact in contrast to the first one. A combination of both strategies seems to be the best choice. Thus, we obtain the fastest retract motion with the ability to fully loose external contact.

After this discussion of a simulation use-case different experiments are described in the following, giving an insight into the injury mechanisms during contact with various sharp tools.

IV. EXPERIMENTS

In this section a set experiments are 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 [27] the dynamics is so fast that a realistic robot is not able to reduce the impact characteristics by the collision detection and reaction. However, during our previous investigations a subjective safe feeling could definitely be experienced by the users. Despite this limitation in reactivity to blunt impacts it was shown as well that the necessity of countermeasures is not absolutely crucial since rigid free impacts pose only a very limited risk at typical robot velocities up to 2 m/s. This is definitely not the case for soft-tissue injuries caused by a stab, since the injury severity due to the penetration can reach lethal dimensions. The particular worst-case depends on the exact location by means of underlying potentially injured organs. Because of the much lower dynamics compared to rigid impacts, the requirements on a reactive robot concerning detection and reaction speed are somewhat relaxed and not unachievable for such situations as exemplified in Sec. III-D. It seems surprising at a first glance that it is not possible to counterbalance rigid blunt robot-human impacts by means of control, which are definitely not life-threatening[6] but at the same time very dangerous or even lethal contacts with tools seem handable to a certain extent. One purpose of the present experiments is to prove this statement.

In the framework of this paper the situation in, which the robot moves in position control with/without collision detection by utilizing joint torque sensing is considered. The contact force is measured with a JR3 Force-torque sensor in the wrist. Please note that this sensor is **only** used for measurement and **not** for collision detection.

A. *Investigated Tools*

The variety of tools one could analyze are basically countless and therefore a selection of tools[7] was carried out, see Fig. 4. We focused especially on sharp ones so to analyze the problem of stabbing. Furthermore, we chose different blade profiles and lengths to analyze cutting, which turned out to be a vast injury threat.

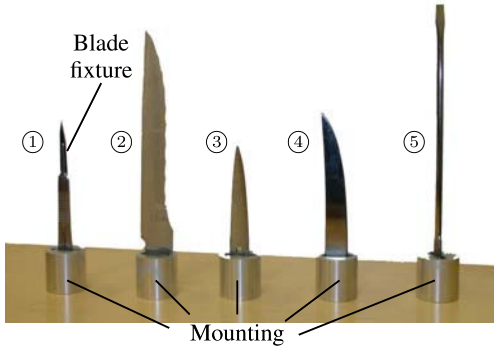

Fig. 4. Investigated tools: ① Scalpel, ② kitchen knife, ③ scissors, ④ steak knife, ⑤ screwdriver.

B. *Silicone Block*

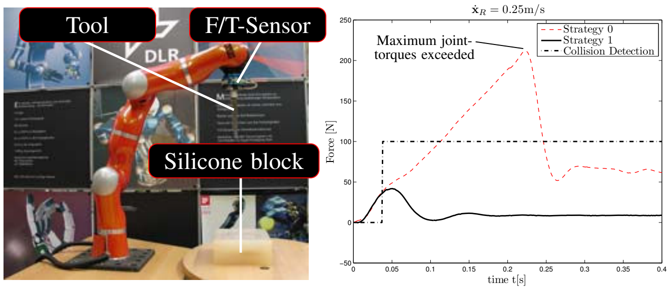

Fig. 5. Stabbing tests with the silicone block and a kitchen knife mounted on the robot.

As a first experimental contact material a silicone block[8] was used in order to get a feeling for the sensitivity and effectiveness of the collision detection and reaction for soft contact, see Fig. 5 (left). Due to its identified properties it can be used as a benchmark material (in contrast to some biological tissue). These first tests were conducted at a Cartesian velocity along z-axis of 0.25 m/s, which is the recommended velocity according to the new ISO10218 for collaborative robots [28]. The mounted tool is the kitchen knife. Figure 5 (right) shows how effective the collision detection and reaction can help to reduce contact forces and the penetration depth. The desired goal configuration $\mathbf{x}_d$ was located at a depth of 8 cm in the silicone block. Without any collision reaction strategy the achieved penetration was 35 mm at a contact force of 220 N with joint six exceeding its maximum joint torque. This causes a low-level safety feature for robot protection to immediately stop the manipulator by engaging its brakes, leading to a force drop is due to the intrinsic joint stiffness of the robot. With activated collision detection and reaction the maximum penetration depth was dramatically reduced to ≤ 6 mm at a contact force of 40 N, i.e. a reduction by a factor of ≈ 5.

C. *Pig Experiments*

In order to obtain results with real biological tissue we conducted experiments with a pig leg, see Fig. 6. From an

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[6] Please note that we refer to impact speeds of up to 2 m/s.

[7] The tools were tested in the same condition they were bought except for the fact they were glued into a rigid mounting to remove eventually beneficial compliances.

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

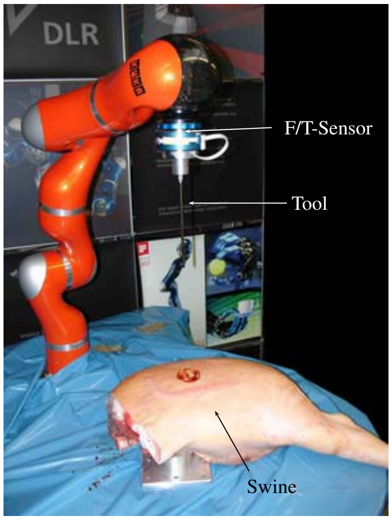

Fig. 6. Testing setup for the pig experimental series.

anatomical point of view pigs are commonly accepted as being very similar to human beings. Both, impact experiments in automobile crash-testing and in forensic medicine use them for first experiments or even for predictions of results with human tissue. Differences to humans and changing tissue properties through mortex are apparent but still it seems to be of immanent importance to conduct experiments with natural tissue. To our understanding these investigations can be fundamental to robotic safety since e.g. classical impact experiments with knifes in forensic medicine as described in [15], [16] did (of course) not take any robot behavior into account, which in turn vastly influences the resulting injury. The robot is equipped with a JR3 force/torque sensor only for measuring the contact force. The stabbing trajectory is a straight line along the z-axis and the desired configuration is slightly above the table. The pig is located on a rigid table, i.e. a clamping scenario is analyzed due to its worst-case properties.

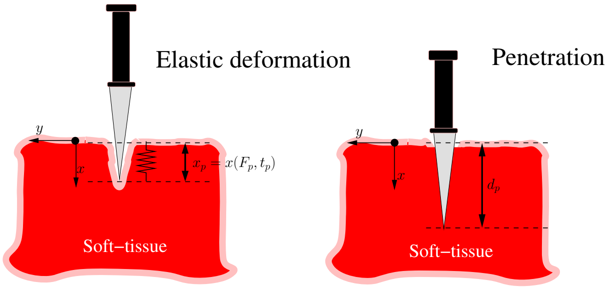

Fig. 7. Elastic deformation and skin penetration

1) Stabbing: Table I and Fig. 8 summarize the outcome of the stabbing tests. The trajectory of the robot was chosen such that it moves on a straight vertical line (compare also Fig. 11) contacting the skin in normal direction with the tool axis. The investigated robot velocities[9] were 0.16 m/s and 0.64 m/s. Surprisingly, with the screwdriver mounted,

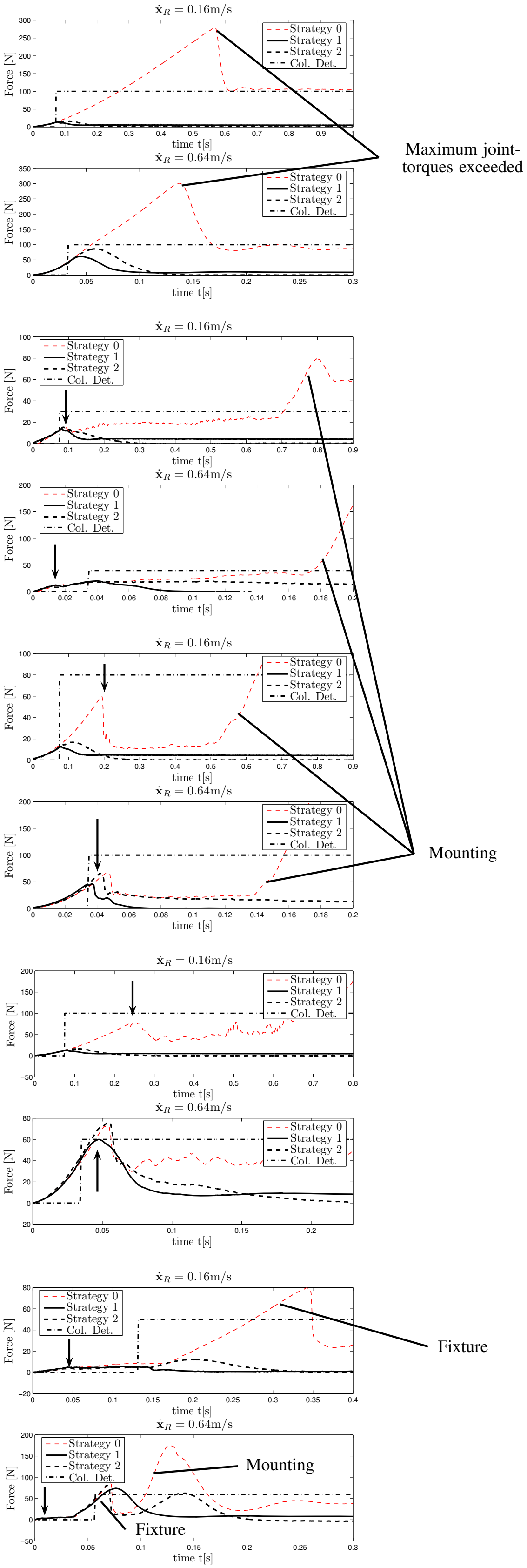

Fig. 8. Results of stabbing tests with and without collision detection for the pig tests. ①: screwdriver, ②: steak knife, ③: scissors, ④: kitchen knife, ⑤: scalpel. The arrows denote the moment of penetration.

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[9] The chosen trajectory was mainly used as a typical representative for normal operation trajectories. For the experiments we present the robot is not able to perform larger Cartesian velocities. For 0.64 m/s some joints begin to deviate from the path due to joint torque/speed saturation.

	$\dot{\mathbf{x}}_R = 0.16$ 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.

the robot was not able to penetrate the pig 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 as described in Sec. IV-B. For the other tools Tab. I gives the measured values for the penetration depth d_p, the penetration time t_p (, which can be interpreted as the *available reaction time* to prevent skin penetration), the penetration force F_p and the elastic deflection before penetration x_p, i.e. the deflection of the skin, which has to be reached with a particular tool for penetration, see Fig. 7.

As shown in Tab. I without collision detection (Strategy 0) all sharp tools penetrate into the tissue with their entire blade length, pointing out the lethality potential. At the same time it can be extracted that at low speeds 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 exact location and ranges from no penetration up to a penetration depth of a few millimeters. For the used 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. 4.

For larger velocities a significant observation, confirming the results from the simulation can be made: Switching to Strategy 2 is causing a higher penetration depth due 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 further penetration of the tissue until the robot's energy is fully dissipated takes place. Furthermore, only Strategy 1 is able to limit the penetration depth to values, which are lethal in absolute worst-case scenarios, i.e. below 2.4 cm. Surprisingly the penetration force seems not to be significantly velocity dependent.

Apart from the characteristic values in Tab. I the force profiles of the stabbing experiments are depicted in Fig. 8. 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. Especially following general aspects become clear when evaluating the plots.

- The moment of penetration is characterized by a significant force discontinuity (drop).
- A very low resistance can be observed from the moment the tool intruded the subcutaneous tissue.
- Force reduction by Strategy 2 is significantly slower compared to Strategy 1 (compare also to Sec. III-D).
- After the initial penetration the contact force increases very slowly compared to the elastic force of the skin.

The influence of the tool mounting (Fig. 4) can be observed for Strategy 0, resulting in a significant increase in force and a compression of the entire subject (the tool mounting establishes a blunt contact). For the scalpel the quite different course needs to be explained in more detail: The very low penetration threshold is followed by an almost constant section, denoting represents the intrusion of the entire blade. For 0.16 m/s the following increase in force is caused by the fixture of the blade, which therefore can be detected. For the graph with an impact velocity of 0.64 m/s the force increase due to the fixture is followed by a second one caused by the mounting as for the previous tools.

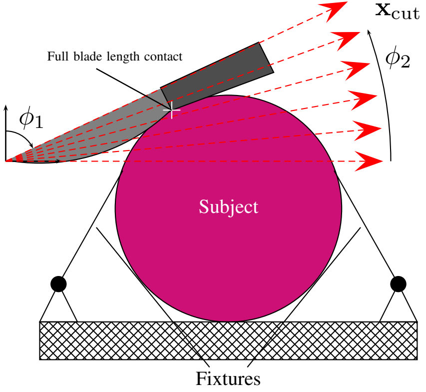

Fig. 9. Cutting trajectories for a fixed subject.

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 tool orientation ϕ_1, the desired cut direction ϕ_2 and the cutting velocity, see Fig. 9. If ϕ_1 is chosen then the pig position is already determined, since the cut shall be carried out with the full available blade length. In our case ϕ_1 was chosen to be $\phi_1 = 30^o$. Investigated tools were the steak knife, the scalpel, and the kitchen knife. The question, which cutting

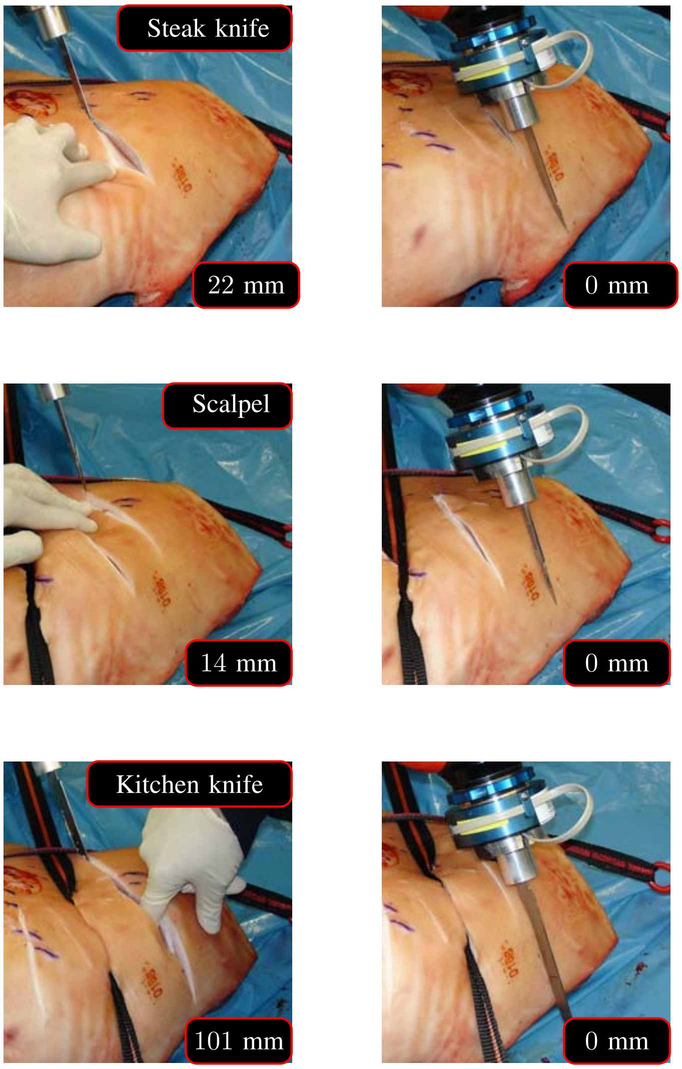

Fig. 10. Resulting injury due to cutting.

angle ϕ_2 is the worst case was answered experimentally and led to $\phi_2 = 10^o$. Furthermore, it became clear to us that cutting velocities must be quite high to cause damage to the skin and the underlying tissue. At a low velocity of $||\dot{\mathbf{x}}_{\text{cut}}|| = 0.25$ m/s more or less no injury was observed and merely a scratch in the skin could be found. However, at $||\dot{\mathbf{x}}_{\text{cut}}|| = 0.8$ m/s this changed drastically. For the cutting trajectory this was the maximum velocity along which the robot could still follow the desired motion without significant lag in some joint, leading to a deviation from the desired motion. Figure 10 (left column) shows the large and deep lacerations caused by all tools if no safety feature is activated. Life-threatening depths can be easily achieved. Please note that the subject is fixed, presumably leading to higher injuries compared to a non-fixed subject. Investigating the effects without constraints on the subject are left for future research. Apparently, the blade length is heavily influencing the resulting laceration depth. Although a scalpel is an extraordinary sharp tool easily penetrating the skin, the small blade length limits the penetration depth to 14 mm. This is almost an order of magnitude smaller than for the large kitchen knife. Thus, for such high robot velocities long-blade knifes are far more dangerous than e.g. scalpels, which in turn are able to penetrate the skin already at quite low velocities.

Though the described large and potentially fatal injuries are possible, the risk can be reduced even at 0.8 m/s by collision detection and reaction to almost neglectable levels at, which no penetration or cut takes place anymore. Even in case of the scalpel we are able to entirely prevent injury of the epidermis, pointing out the surprisingly high sensitivity of our collision detection, see Fig. 10 (right column).

Summarized following main conclusion for cutting can be drawn:

1) Injuries caused by cutting can reach severe and even lethal levels at high velocities. At low velocities the epidermis is hardly injured.
2) The achieved level of injury mainly depends on the blade length and the cutting velocity.
3) Collision detection based on joint torque sensing is a very effective countermeasure to entirely prevent injuries from cutting even at quite high velocities.

After this in-depth evaluation of soft-tissue injuries caused by sharp tools we were confident enough to exemplify the effectivity of the collision detection with a human volunteer.

D. The most convincing argument

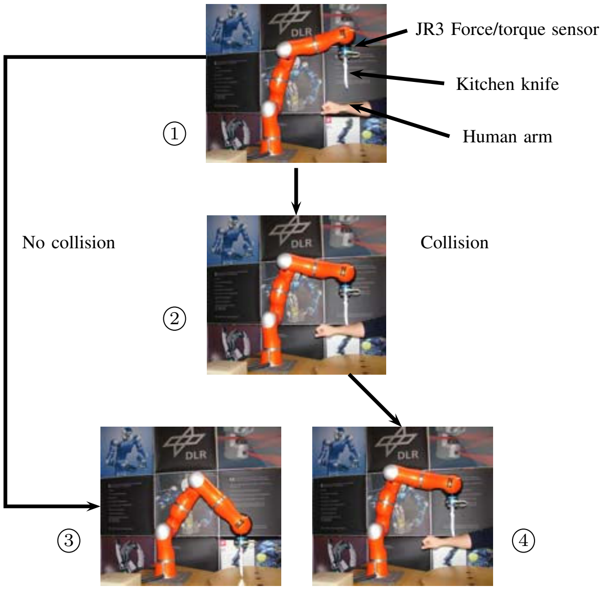

Fig. 11. Effectiveness of the collision detection and reaction with a human.

Since the presented experiments showed 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 against the moving robot with a mounted knife[10], see Fig. 11. A full evaluation for the case of free stabbing still has to be carried out but it will be definitely less dangerous compared to the constrained stabbing presented in this paper. The robot velocity was chosen to be $\dot{\mathbf{x}}_R \in \{0.1\ 0.25\ 0.5\ 0.75\}$ m/s. In Fig. 12 the measured force during the collision with the human is

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[10] The subject formally confirmed that he was happy to take part in the experiment and that he is happy to be shown on the attached video.

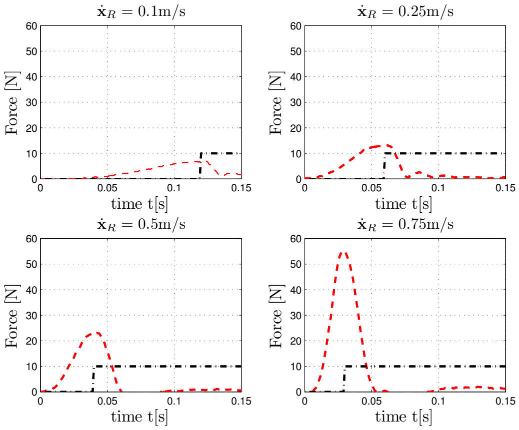
$\dot{\mathrm{x}}_R = 0.1\mathrm{m/s}$ $\dot{\mathrm{x}}_R = 0.25\mathrm{m/s}$ $\dot{\mathrm{x}}_R = 0.5\mathrm{m/s}$ $\dot{\mathrm{x}}_R = 0.75\mathrm{m/s}$

Fig. 12. Contact forces for stabbing tests in free space with human volunteer.

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 0.75 m/s a minimal scratch in the epidermis could be observed. This experiment strongly supports the results obtained from simulation and experimental evaluations. It points out that, although intuitively it seems very unrealistic to prevent injury from humans during sharp contact by means of control, there is a clear chance to greatly reduce danger to the human even up to velocities of 0.75 m/s.

V. CONCLUSION

In this paper experimental fundamentals for evaluating soft-tissue injuries in robotics were created. Various increasingly sharp tools ranging from a screwdriver to a scalpel were analyzed and we proved the large benefit of our collision detection and reaction schemes. A video showing the experiments discussed in this paper is attached.

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