The Role of Compliance in Robot Safety

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Abstract— **In situations where robots share their workspace with humans, and where physical human-robot interaction is possible or even necessary, safety is of paramount importance.**

Low weight and passive compliance are often considered important aspects contributing to robot safety. In this paper, the role of passive compliance is investigated with respect to the safety of a 2-DOF pneumatically actuated arm. By combining measurements and impact simulations, the safety of the system is evaluated for a wide range of joint stiffnesses.

It turns out that passive compliance plays a double role: it improves safety in some impact situations, but its capacity to store energy can also be dangerous.

I. Introduction

Historically, one of the prime reasons for the introduction of robots in industrial applications was to remove human operators from potentially hazardous work environments. Paradoxically, the robots themselves also pose a threat to workers. The design and control of industrial robots are optimized for performance, which provides them with a high speed of execution, high accuracy and high repeatability. Their high weight, high speeds, stiff characteristics and high gain control make them dangerous if a collision with a human should occur. For this reason, people are not allowed in the vicinity of a robot while it is working.

Over the last few years, the evolution in new and envisaged robotic applications requires increasingly closer contact between humans and robots. There is a growing interest in robots that operate in the close vicinity of people, or even physically interact with them. The spectrum of possible applications includes rehabilitation robots (to help people relearn motor skills they've lost in an accident or due to stroke, for instance), robotic prostheses, robot assistants for helping the elderly, manufacturing (with human-robot collaboration), entertainment robots, wearable robots, etc.

The requirements for the new generation of robots are fundamentally different. Unlike industrial robots, they will function in unstructured environments, and have only partial knowledge of their surroundings. Since contact between the robot and objects or people surrounding it is possible, safety is the most important requirement.

Making robots sufficiently safe and dependable to be suitable for physical human-robot interaction is a challenge. It requires the combination of lightweight materials, new actuators, soft-robotics features and adapted control strategies.

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In literature, low weight and passive compliance are often considered to improve robot safety. In this paper, we study the role of passive joint compliance in the safety of a lightweight 2-DOF robot.

Section II gives a brief overview of robot safety, specifically the quantification of safety and how safety aspects influence design and control. Following a very short introduction to the pneumatic manipulator (section III), section IV explains how safety was evaluated in this work. In section V the influence of compliance is analysed, and section VI provides the conclusion.

II. Robot safety

Most robots in use today operate behind secure barriers that keep people outside of the work envelope [1], [2]. In applications that involve close contact or cooperation between humans and robots, this principle of "safety by segregation" is no longer useful [3], [4]. It is clear, however, that without concrete safety guarantees robots cannot be allowed to work in close proximity to humans. In this context, safety becomes more important than traditional robot performance criteria such as speed and accuracy. Combining safety and performance is an important challenge in the design of human friendly robotic systems.

Robot safety in general is very broad (see for instance [5]), and covers many aspects ranging from mechanical design over software reliability, compliant coverings and avoiding sharp edges to psychological issues (letting people know which safety features are in place, for instance). An important factor in practice is also the dependability [6], [7] of all components and the system as a whole (i.e. it should be able to deal with sensor failure, actuator failure, software failure, etc.). In this work, we will only consider safety, not dependability.

A. *Quantifying safety*

In the context of physical human-robot interaction, safety is interpreted in terms of the injuries sustained by the human in case of a collision with the robot. In order to evaluate safety of existing robots, or to optimize robot design or control for safety, the concept has to be defined quantitatively.

Quite some work exists that involves quantitative measures of safety, danger, injury or pain in the context of human-robot collisions [8], [9], [10], [11], [12], [13], but no universally accepted method of quantifying safety exists today. One mostly relies on injury severity indices developed in the automobile industry (cf. [14], [15]). By far the most popular is the Head Injury Criteria or HIC [16], which was introduced to robotics in [17], [18]. It is defined as

$$\mathrm{HIC} = \max_{\Delta t} \left\{ \Delta t \left(\frac{1}{\Delta t} \int_{t_1}^{t_2} \|\ddot{\boldsymbol{r}}_H\| \, dt \right)^{2.5} \right\} \tag{1}$$

with $\Delta t = t_2 - t_1 \leq 36\,ms$. $\|\ddot{\boldsymbol{r}}_H\|$ is the magnitude of the head acceleration that results from the collision, and is measured in multiples of $g = 9.81\,m/s^2$.

Mappings exist to translate HIC values to the probability of sustaining an injury of a certain level, with the levels usually expressed in terms of the Abbreviated Injury Scale (AIS), [19]). Recent research that considers impacts between robots and crash-test dummies (both experimental and in simulation) shows that the mapping of HIC to injury level used in the automobile industry cannot simply be applied in robotics [15], [20]. The main reason is that human-robot impacts occur at much lower velocities than the ones typically encountered in the car industry. The HIC can still be used to compare levels of safety, though.

Since the HIC does not provide an "absolute" measure of danger, we use the maximum interaction force that occurs during a robot – head collision as a measure of danger in this paper.

B. Design and control for robot safety

It was shown in [21] that industrial robots are considerably less dangerous than previously assumed in case of collisions without clamping (i.e. when no part of the body is being squeezed between the robot and a part of the environment (a wall, for instance)). More specifically, the authors state that "blunt head impacts without clamping at moderate[1] robot speed are, no matter how massive the robot is, very unlikely to be life-threatening".

It is clear that there is still a long way to go between "unlikely to be life-threatening" and "suitable for physical human-robot interaction". Robots that interact directly with people are designed in a different way than conventional (industrial) robots. The two main design criteria that influence safety are:

- Low weight – robots designed to be used in contact with humans typically have low inertia of the moving parts (which limits damage in case of collisions). Examples are the DLR-LWRIII lightweight arm [22] and the Whole Arm Manipulator (WAM, [23]).
- Passive compliance – compliant elements in the robot structure decouple the inertia of the impacting link and that of the rest of the robot (i.e. the other links and (in case of electrical actuation) the rotor inertia of the motors). This means that mainly the impacting link is felt, and only a fraction of the inertia of the rest of the robot.

  A popular way to introduce compliance is by means of compliant actuators. An overview of compliant actuators is given in [24].

  It should be noted that passive compliance isn't always the result of deliberately introducing elastic elements. It can also be a by-product of a lightweight design or the use of certain transmissions (e.g. harmonic drives or cable transmission) or sensors (e.g. torque sensors), as is the case for the LWRIII. When this is the case for lightweight robots not specifically designed for human interaction it is seen as a disadvantage since mechanical compliance (whether it is introduced on purpose or not) generally degrades robot performance in the traditional sense (i.e. speed and accuracy). In the case of rigid links and flexible joints with constant stiffness, specialized controllers are available (see for instance [25], [26], [27], [28]) to minimize performance loss.

  Since it was shown that increasing joint compliance beyond the level naturally present in the LWRIII doesn't diminish injury potential [15], [29] propose to use compliant joints as a way of protecting the robot against impacts (which may break gears, sensors etc.), much more than the human.

[1]Moderate can be interpreted here as up to 2 m/s.

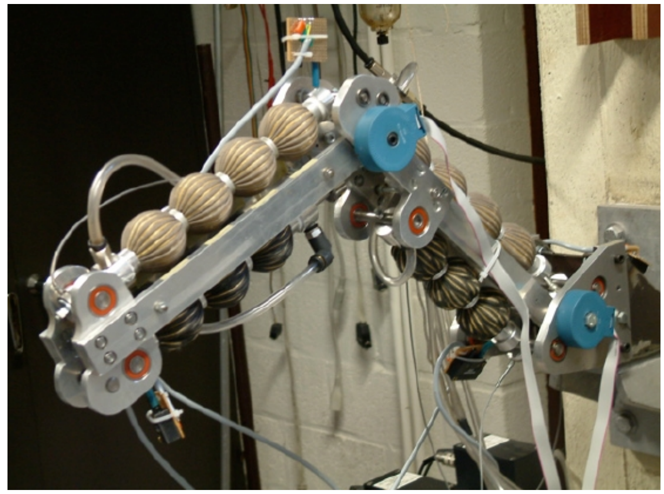


Fig. 1: The PPAM-actuated manipulator.

The most often used control strategy for physical human-robot interaction is probably impedance control [30] and its variants, but other methods exist as well. In general, robots are controlled to move relatively slowly when interacting with people, which reduces impact velocity in case of collision. References that discuss control in a safety context include [9], [31], [12], [32], [33], [28], [34], [35].

All control based safety methods are inherently limited by the available control, actuator and sensor bandwidth, though. In case of a sudden impact, they may not be able to respond fast enough, which means that the natural impedance of the robot will be felt. This can be dangerous for the human, but also for the robot [15], [29].

Integrated approaches that combine specialized hardware and control techniques to improve safety but maintain performance have been reported as well. Distributed Macro-Mini actuation (DM^2, [17], [36], [37]) consists of partitioning the actuation into separate macro and mini actuators (used in parallel) that provide for low- and high frequency torque generation, respectively. The mini actuators are small motors

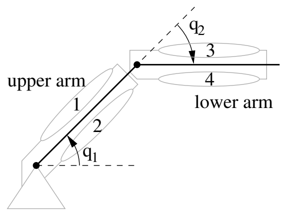


Fig. 2: The elbow-up configuration.

on the joints, the macro actuators are series elastic actuators [38] placed at the base, at least in the initial concept. In more recent work pneumatic artificial muscles were used as macro actuators [39], [40].

Another integrated design/control approach is variable stiffness or more generally variable impedance actuation (VIA, [41], [42], [18], [43]). VIA uses fast and continuous changes of joint impedance to provide user safety at all times while maximizing (under the constraint of safety) control performance. An important result is the "Fast and soft" concept [18]. It states that in order to guarantee a (chosen) maximum level of injury risk, joint compliance should be high when moving fast, and can be low when moving slowly.

III. Pneumatic Manipulator

The work regarding safety presented in this paper is based on measurements taken using a small and lightweight 2-DOF pneumatic manipulator actuated by a series arrangement of Pleated Pneumatic Artificial Muscles (PPAMs, [44], [45]). The system is shown in fig. 1. Figure 2 shows the conventions used in the rest of this document regarding to how both joint angles are defined.

The inherent compliance of these actuators, combined with the very low total weight of the system ($\approx 2.6\,kg$) provide the system with excellent hardware safety features.

IV. Safety of the Pneumatic Manipulator

The pneumatic manipulator studied in this work fulfills the principal design requirements of a "safe" robotic system. With a total mass of around 2.5 kg for the moving parts it can be considered lightweight. It also has highly compliant joints due to the PPAM actuators, i.e. the system is passively compliant.

In previous work, it was shown that hardware safety alone is not enough [46]. When under PID control, the system can be unsafe if the target position is discontinuously changed. If we suddenly change the desired value for q_1, and assume that a collision between the robot and a human head occurs in the subsequent step response, simulations show a maximum impact force of $1524\,N$. This force high enough to break several bones in the face [19]. Due to its slow response to large position errors, the use of Proxy Based Sliding Mode Control (PSMC, [33]) can greatly increase the system safety in situations like this.

It is clear that with proper path planning, sudden changes in desired position or trajectory don't occur. This doesn't mean they are impossible, though. A typical example is when someone pushes the arm away from its desired position (which is possible due to its compliance), and then suddenly releases it. Under standard PID control, it would much more violently than with PSMC. Another possibility is a problem with the supply of compressed air (due to closing a wrong valve, for instance). Cutting the air supply is not in itself unsafe in this case: due to leaks and valve control actions, the actuators slowly lose pressure, causing the system to gently "relax" and the position error to increase. At repressurization, however, the large position error could cause a violent reaction.

The maximum impact force of $1524\,N$ when using PID control was calculated using the joints' actual stiffnesses, which are very low (close to 40 Nm/rad for the first joint and close to 30 Nm/rad for the second). In this study, we investigate the influence of joint stiffness by varying the joint stiffnesses used in impact simulations.

A. Experiment

The initial values (of position and velocity) for the impact simulations are taken from experimentally measured data, in this case using a PID controller with gravity compensation (cf. [46]). The dataset that was used was generated by switching the desired value for q_1 discontinuously between $30\pi/180$ and $70\pi/180$, while the desired value for q_2 was kept constant at $-80\pi/180$. The angles recorded during this step response are shown in fig. 3, the measured angular velocities are shown in fig. 4.

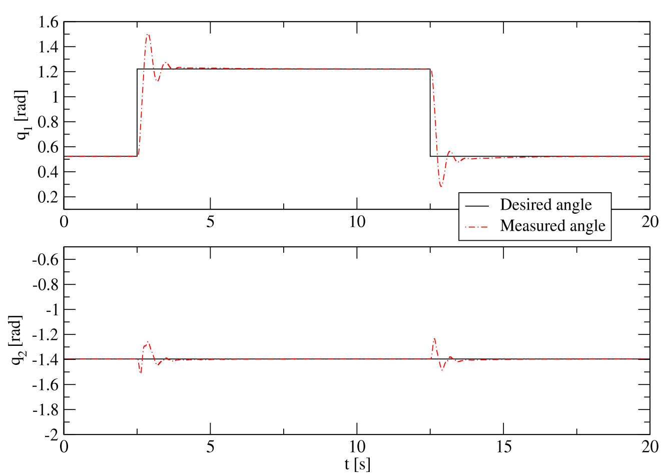
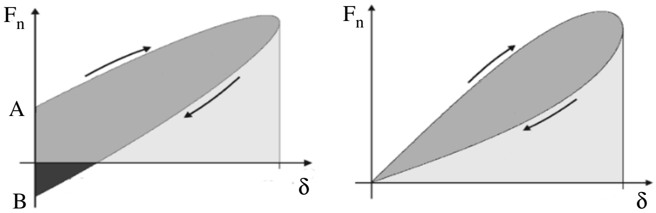


Fig. 3: System response to a step change in desired angle values (while using PID control).



(a) Kelvin-Voigt (b) Hunt-Crossley

Fig. 5: Hysteresis loops in the F_n-δ plane generated by a collision. Figures adapted from [47].

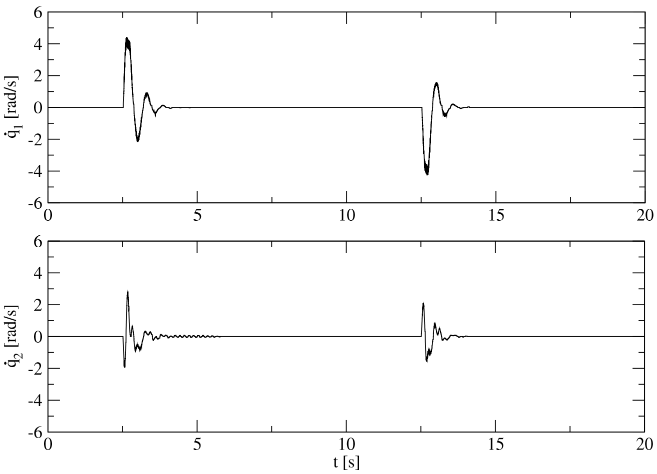


Fig. 4: Angular velocity measured for the step responses shown in fig. 3.

B. Contact model

In order to simulate a collision, it is necessary to model the contact between head and robot. One of the simplest models to describe the relation between the relative penetration of two bodies and the resulting contact force is the Kelvin-Voigt model, which consists of the parallel connection of a (linear) spring and a (linear) damper:

$$F_n = \begin{cases} k\delta + b\dot{\delta} & \delta \geq 0 \\ 0 & \delta < 0. \end{cases}$$

In this equation, F_n is the normal contact force between the bodies, and δ is the relative indentation. An impact generates a hysteresis loop in the F_n-δ plane, as shown in fig. 5a. Although popular because of its simplicity, the model has some physical inconsistencies [48], [47]. The most obvious ones are the discontinuity of the contact force at impact (point A), and the "sticky" negative force as the objects are separating (point B). Both inconsistencies arise at small penetration depths, since there F_n is mainly determined by the damping term.

By making the viscous damping dependent on the penetration depth, as proposed in [49], these problems can be overcome:

$$F_n = \begin{cases} k\delta^n + b\delta^n\dot{\delta} & \delta \geq 0 \\ 0 & \delta < 0. \end{cases} \tag{2}$$

The exponent n is usually close to 1, and takes into account the stiffness variation due to the fact that the contact surface area increases with increasing penetration depth.

In [15], the parameters k, b and n of the Hunt-Crossley model (2) were estimated from impact experiments between the LWRIII lightweight arm and the head of a Hybrid III crashtest dummy. The impact characteristics of the Hybrid III's head are comparable to those of the human frontal area [19].

These parameters are crucial to simulate realistic impacts, and hence to determine realistic safety characteristics.

C. Simulation

The collision simulations were performed using approximate models for both the manipulator and the head. The manipulator was modeled as an unactuated 2-DOF flexible joint arm with constant joint stiffnesses. The influence of gravity was not taken into account (i.e. the impact was assumed to happen in the horizontal plane). The initial values of the arm-model in the simulation (i.e. the initial angles and angular velocities) were taken from measured data (cf. figs. 3 and 4). The mass of the head was chosen to be 5 kg, and it was assumed that the head's motion after the collision is unrestrained by either the environment or the rest of the body. This is a justified assumption, since it is reported that for short impacts the neck has little influence on the motion of the head immediately after impact [20], [50].

Specifically, in order to calculate the HIC value for a hypothetical collision at time t_0 using the data measured in an experiment, the following procedure was used:

- The initial position and angular velocity of the simulated model's links are set to the ones that were actually measured at t_0.
- Both joint stiffnesses are set equal to a predetermined value k, and are assumed to remain constant during the collision.
- The head is positioned so that it just touches the manipulator's tool-center point at t_0, but there is no interaction force between them. In order to obtain the highest possible HIC value, the center of mass of the head is placed in the direction of the Cartesian velocity vector of the TCP at t_0. In other words, the vector $\boldsymbol{r}_{TCP\rightarrow G}$, that defines the location of the head's center of mass G at t_0 with respect to the TCP, is parallel to $\dot{\boldsymbol{r}}_{TCP}$, the Cartesian velocity of the TCP at t_0. This is illustrated in fig. 6.
- The motion of the whole system is simulated for a period of $50\,ms$. The head acceleration is then used to calculate the HIC and the impact force.

Since an impact simulation and the maximization involved in calculating the HIC takes some computing time, we did not simulate a possible collision at each timestep of the measured dataset. Instead, for each value of k, the HIC was calculated at four different instants: the time of maximum recorded Cartesian velocity of the TCP, the time of maximum recorded angular velocity of both links, and the time of the maximum recorded value of $\|\dot{\boldsymbol{q}}\|$, with $\dot{\boldsymbol{q}} = \begin{bmatrix} \dot{q}_1 & \dot{q}_2 \end{bmatrix}^T$. The highest

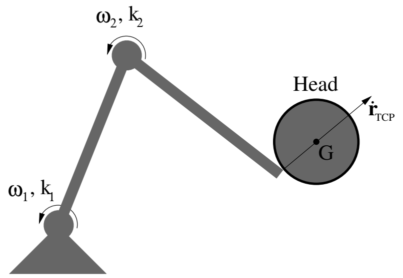


Fig. 6: Position of the head at the start of the impact simulation.

obtained value of the impact force is then retained for that stiffness value k.

D. Limitations

It should be noted that the method used to evaluate the safety of the system for a given value of joint stiffness has certain limitations:

- As in most robot safety studies, it only considers the initial impact (only the first 50 ms after impact were simulated, inspired by the definition of the HIC). Of course, overall safety will also depend on what happens after impact. It has been shown on the LWRIII that if the robot detects the impact and responds appropriately, contact forces can be significantly reduced [35], for instance.
- Clamping was not considered, although it is more dangerous than an unconstrained collision [51]. Since the danger in clamping situations is highly dependent on robot mass, the pneumatic manipulator is expected to be on the safe side with its total mass of around 2.5 kg.
- Only blunt impacts were considered, no sharp edges or sharp objects attached to the robot. It is clear that these could greatly increase the danger of any robotic system.
- No hardware or software errors were considered. It was assumed that all sensors, actuators, controllers, electronics etc. are working. Since it was previously shown that the system can be unsafe when under PID control, we can assume that it will also be unsafe in case of serious software errors in the controller.

V. Influence of joint compliance

In order to investigate the influence of joint compliance (the inverse of stiffness), the simulations for the step-response (which was found to be the most unsafe in the previous section) were repeated, but with modified joint stiffnesses. Both joints were set to the same stiffness k, and k was varied between 1 Nm/rad and 6000 Nm/rad. The upper limit of 6000 Nm/rad is in the range typically encountered in flexible joint robots [52]. The resulting impact force is plotted as a function of k in fig. 7.

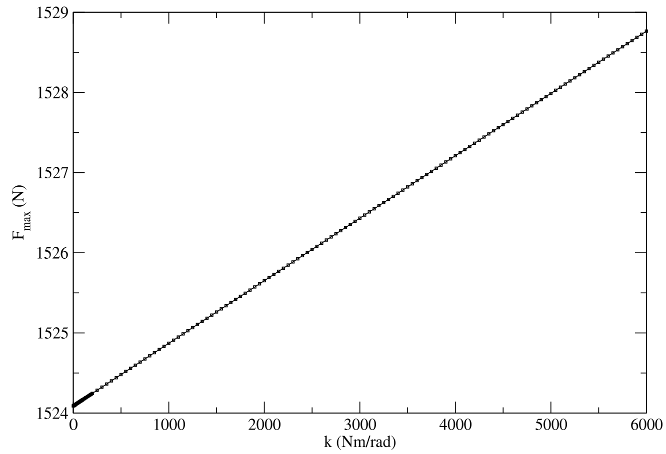


Fig. 7: Maximum interaction force in case of a robot-head collision during the step response of fig. 3 as a function of joint stiffness k.

We see that $F_{\max}$ hardly changes as the joint stiffness becomes higher: an increase of less than 5 N (or 0.33 %) for an increase of 5999 Nm/rad in joint stiffness. Even for the high range of stiffnesses (which could never be achieved with PPAMs), the impacting link is effectively decoupled from the rest of the system. The impact force is almost exclusively determined by the inertia of the impacting link. This is consistent with the findings of [15], [29].

It seems that passive compliance plays a double role in robot safety. On the one hand, it can protect both human and robot in some impacts situations. This could be the case for instance if the robot is in normal operation and moving slowly, but collides with a fast moving human. On the other hand, the compliant elements can store energy, which (when released) can lead to higher speeds, and thus higher danger, than would be the case without compliant actuators. This "strikeout" feature is used to greatly increase the throwing distance of a ball by [53], [29], and to increase the jumping height of a robot by [54]. The effect is also present in the step response of the manipulator. We can see this by looking at figure 8, which shows a small part of fig. 4 (only the part corresponding to the upward step in q_1, while the desired value of q_2 remains constant, cf. fig. 3).

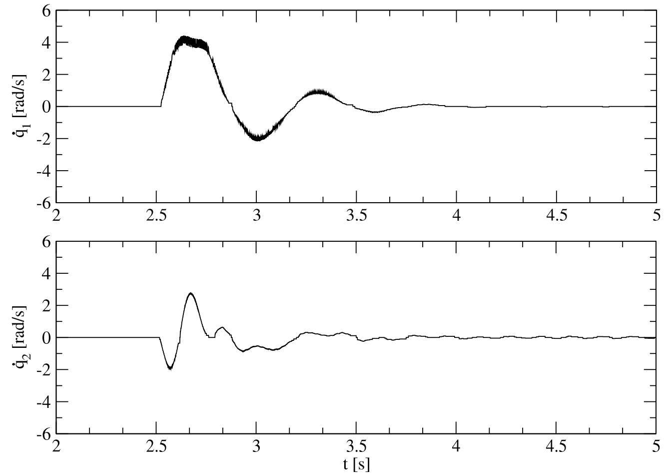


Fig. 8: Angular velocities measured for the step response shown in fig. 3.

Wee see that as q_1 start to rise ($\dot{q}_1 > 0$), q_2 decreases ($\dot{q}_2 < 0$). In this phase, the "spring" of the second joint is being loaded. Soon after, $\dot{q}_2$ starts increasing, as the spring releases its energy[2]. The consequence is that both $\dot{q}_1$ and $\dot{q}_2$ are close to their maximum simultaneously for a short period of time, which results in a high end-effector velocity, and hence a high impact force in case of collision.

VI. Conclusion

In this paper, impacts between a pneumatic manipulator and a human head were simulated for varying values of joint stiffness. The response of the head at the time of impact and immediately afterwards was calculated. Safety was evaluated by means of the maximum impact force.

Varying joint stiffness from 1 Nm/rad to 6000 Nm/rad had virtually no influence on the maximum impact force. Thus, the maximum impact force turned is almost independent of joint stiffness over a wide range of stiffnesses. This indicates that, as long as some passive compliance is present, the impact is mainly determined by the inertia of the impacting link itself, not by the rest of the robot. Even a very limited amount of compliance improves safety in case of collision.

On the other hand, compliant elements can store energy. When suddenly released, this can lead to higher impact speeds, and consequently more danger.

We see that passive compliance can be regarded as a double edged sword with respect to robot safety. It can improve safety in some cases of sudden impact, but its ability to store and subsequently release energy can also make it more dangerous.

Acknowledgements

It is gratefully acknowledged that S. Haddadin provided the values of k, b and n (cf. eq. (2)) that were estimated as described in [15].

[2]Of course, passive compliance isn't the only factor in this behavior, the controller of joint 2 also contributes as it tries to keep q_2 constant.

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