Physical Human-Robot Interaction: Dependability, Safety, and Performance

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***Abstract*— Robots designed to share an environment with humans, such as e.g. in domestic or entertainment applications or in cooperative material-handling tasks, must fulfill different requirements from those typically met in industry. It is often the case, for instance, that accuracy requirements are less demanding. On the other hand, concerns of paramount importance are safety and dependability of the robot system. According to such difference in requirements, it can be expected that usage of conventional industrial arms for anthropic environments will be far from optimal. An approach to increase the safety level of robot arms interacting with humans consists in the introduction of compliance at the mechanical design level.**

In this paper we discuss the problem of achieving good performances in accuracy and promptness with a robot manipulator under the condition that safety is guaranteed throughout whole task execution. Intuitively, while a rigid and powerful structure of the arm would favor its performance, lightweight compliant structures are more suitable for safe operation. The quantitative analysis of the resulting design trade-off between safety and performance has a strong impact on how robot mechanisms and controllers should be designed for human-interactive applications. We discuss few different possible concepts for safely actuating joints, and focus on aspects related to the implementation of the mechanics and control of this new class of robots.

I. Introduction

Physical Human-Robot Interaction (pHRI) represents one of the most motivating, challenging and ambitious research topics in robotics. Many of the future and emerging applications of robotics, be they in service [11], care and assistance [9], rehabilitation [14], or in more traditional working contexts [20], will indeed require robots to work in close proximity if not in direct contact with humans.

A robot for pHRI applications must be regarded to all effects as a safety-critical system, as it has been unfortunately proven several times in the past, conventional robots can be dangerous, and even deadly machines [19]. Since the very beginning of industrial robotics, a great deal of attention has been paid to robot safety, the first line of defence having always been to take all measures to enforce segregation between robots and people [2], [5]. As market pressures, together with ethical concerns are about to topple some of the barriers separating robots and people, improoved safety standards are evolving. The 2006 revision of the ISO10218-1 standard [16], for instance, introduces more advanced concepts than in the past, such as the idea of a *collaborative operation* between humans and robots, and the replacement (albeit to a very limited and conservative extent) of fixed rules with *risk assessment* procedures. More generally, for applications involving physical human-robot interaction, analysis tools are needed that are classical in the literature on critical systems [1], [13], [18], but are still rather new in robotics [7], [10], [26], [6]. These tools focus on attributes that return the ability of the system to behave as expected for a given operational scenario. Several attributes exist, depending on context and application: *safety*, i.e. the absence of damages and injuries, *reliability*, the continuity of service, and *availability*, the readiness of service: in a word, the comprehensive attribute of *dependability* (see [1]).

As an answer to the need of building robots that can provide useful performance while guaranteeing safety against all odds, engineers have proposed several innovative solutions to overcome the classical paradigm "rigidity by design, safety by sensors and control" — more suited for conventional industrial robotics — and are shifting towards a "safety by design, perfomance by control" philosophy (viz. [11], [15], [22]). In our previous work [3], [4], VSA (Variable Stiffness Actuation) and its generalization in VIA (Variable Impedance Actuation) have been demonstrated to be effective in obtaining a safe yet performing robot motion by swiftly alternating "stiff and slow" and "fast and soft" motion modes. What distinguishes this approach from several other joint compliance variation schemes (see e.g. the survey paper in this special issue) is that in VSA joint stiffness values are continuously varied as a function of joint velocities, while other methods may adapt compliance only once for each different task. This implies that implementation of VSA requires hardware capable of changing stiffness with a time-constant comparable to that of the mechanics of the rigid robot (i.e., of the order of milliseconds).

Among several possible solutions to implement VSA, we will focus our attention here on the notable class of *antagonistic actuation* (AA) systems. Agonist-antagonist actuator pairs are commonly seen in nature, and have been studied in biomechanics as well as robotics since long time [12]. Compared to conventional rigid robot joints, artificial AA systems are more complex in design, construction and operation. Such increase in design complexity, while useful for achieving a safer system in nominal conditions, might affect the dependability attributes and the performance in presence of faults.

This paper describes possible implementations of the VSA concept via three different arrangements of the Agonist-Antagonist actuation scheme, and provides some elements for a comparison of their dependability, safety, and performance.

II. VSA: Mechanics and Control Co-Design

In a conventional robot link, the effective rotor inertia of the actuator is typically large w.r.t. the link's own inertia, due to the large gear ratios used in robotics, and is responsible of most of the potential damage done in impacts. Limited actuator torques and finite transmission bandwidth prevent policies based on active impact sensing to perform safely enough. Introducing transmission compliance reduces the effects of the rotor inertia in impacts, but also reduces accuracy and swiftness of motion. To overcome these limitations, the use of variable stiffness actuation was proposed in [3], which is based on the intuitive idea of controlling the joints with a high stiffness in slow motion phases when accuracy is needed, and allow substantial joint compliance when motion is fast.

Such *stiff-and-slow / fast-and-soft* paradigm was supported in [3] by a detailed mechanism/control co-design optimization analysis, based on the solution of the so-called *safe brachistochrone* problem, i.e. a minimum time control problem with constraints on the maximum acceptable safety risk at impacts. The ideal VSA model considered in [3] (depicted in fig.1) assumes the possibility to directly impose the desired transmission stiffness changes. This is clearly not physically realizable in mechanical systems: we will consider here more realistic models of VSA systems, and discuss the application of the same design methodology in this setting.

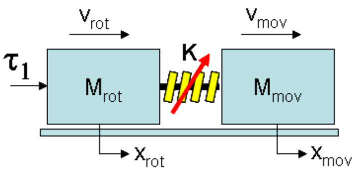


Fig. 1. An ideal model of a Variable Stiffness Actuation mechanism, consisting in a spring whose stiffness can be freely set and changed by an external command.

Among the several possible practical implementations of the VSA concept, we focus on antagonistic realizations. The dynamical model of a simple agonist-antagonist VSA mechanism using two conventional motors connected to the link via two non-linear elastic elements is depicted in fig.2. However, antagonistic VSA systems may assume more general configurations than this one. For instance, in the prototype of antagonistic VSA system depicted in fig.3 ([23]), the two actuators operate through non-linear elastic elements on the link, but they are also connected to a third elastic element cross-coupling the actuators.

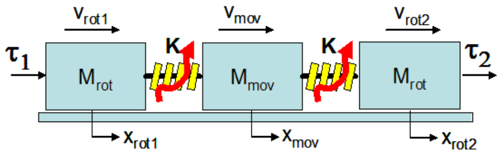


Fig. 2. A simple antagonistic implementation of the VSA concept. Effective rotor inertias are coupled to the link inertia through nonlinear springs.

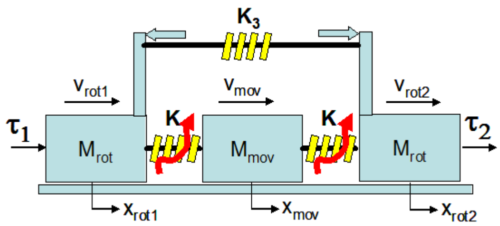


Fig. 3. Another possible antagonistic implementation of the VSA concept, with a third elastic element cross-coupling the two motors.

A. Optimal Control of Antagonistic Actuators

Questions we consider in this section are the following: Is the stiff-and-slow/fast-and-soft control paradigm still valid? Are the good safety and performance properties of the ideal VSA device in fig.1 retained by an antagonistic implementation as the one in fig.2? And what is the role, in antagonistic VSA actuators, of cross-coupling elastic elements, as in fig.3?

To answer these questions, we look again at the solution to the safe brachistochrone problem, which consists in finding the optimal motor torques τ_1, τ_2 which drive the link position x_{mov} between two given configurations in minimal time, subject to the mechanism's dynamics, motor torque limits, and safety constraints. This problem is formalized for the antagonistic mechanism of fig.2 as

$$\begin{cases} \min_\tau \int_0^T 1 \; dt \\ M_{rot1}\ddot{x}_{rot1} + \phi_1(x_{rot1}, x_{mov}) = \tau_1 \\ M_{rot2}\ddot{x}_{rot2} + \phi_2(x_{rot2}, x_{mov}) = \tau_2 \\ M_{mov}\ddot{x}_{link} - \phi_2(x_{rot2}, x_{mov}) - \phi_1(x_{rot1}, x_{mov}) = 0 \\ |\tau_1| \leq U_{1,max} \\ |\tau_2| \leq U_{2,max} \\ \Sigma(\dot{x}_{mov}, \dot{x}_{rot1}, \dot{x}_{rot2}, \phi_1, \phi_2) \leq \Sigma_{max}, \end{cases} \tag{1}$$

where M_{mov}, M_{rot1}, M_{rot2} are the inertias of the link and the rotors (effective, i.e. multiplied by the squared gear ratio); $U_{i,max}, i = 1, 2$ is the maximum torque for motor i, and ϕ_i, $i = 1, 2$ represent the stiffness of deformable elements as functions of the position of rotors and link. A polynomial nonlinear model is used for stiffness, whereby the applied force as a function of end-point displacement is

$$\phi_j = K_1(x_j - x_k) + K_2(x_j - x_k)^3. \tag{2}$$

This model has been found to fit well experimental data for the devices described later in this paper. The safety constraint $\Sigma(\dot{x}_{mov}, \dot{x}_{rot1}, \dot{x}_{rot2}, \phi_1, \phi_2) \leq \Sigma_{max}$ describes the fact that some severity index Σ relative to an hypothetical impact at any instant during motion, should be limited. Severity indices for impacts, and their relation to injury risk levels, have been extensivelty studied in the automotive crash-test industry ([25]) and other domains such as e.g. bio-mechanics of sports. Much work is still needed to understand the implications of different indices and estabilish suitable modifications to adapt to robotics [8]. However, the classical *Head Injury Criterion* (HIC) index, which is used in standardized automotive crash-tests, still provides a very useful reference. The HIC formula is given by

$$\begin{aligned} HIC = \quad & \max_{t_1,t_2} \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} |\ddot{x}_{head}(t)| dt \right]^{2.5} \right\}, \\ & 0 \leq t_1 \leq t_2 \leq T_{max}, \end{aligned}$$

where T_{max} is the time duration of the impact, conventionally set to 15ms or to 36ms. For reference, if the acceleration is measured in g, a value of $HIC_{36} \approx 100$ $g^{2.5}s$ is obtained if the head impacts a rigid wall at a fast walking speed of 2m/s; if acceleration is measured in m/s^2 (as we will do in the sequel), a scaling factor of ≈ 300 applies. The HIC depends on both the velocity of the impacting mass, its inertia and the effective inertia of rotors as reflected through the transmission stiffness. We will use the HIC formula for specifying the safety constraint, i.e. $\Sigma(\dot{x}_{mov}, \dot{x}_{rot1}, \dot{x}_{rot2}, \phi_1, \phi_2) = HIC_{36}(\cdot)$. Note that this can only be evaluated numerically for all but trivial cases.

Different solutions of problem (1) have been obtained numerically, setting parameters to the following values: $M_{mov} = 0.1$ Kgm^2, $M_{rot1} = M_{rot2} = 0.6$ Kgm^2, $HIC_{max} = 100\frac{m^{2.5}}{s^4}$, $U_{1,max} = U_{2,max} = 7.5$ Nm. A first interesting set of results is shown in fig.4. The optimal profiles of link velocity and joint stiffness (σ) are reported for the case where both the initial and final configurations are required to be stiff ($\sigma_0 = \sigma_f = 16$ Nm/rad, plots a and b) and when both are compliant ($\sigma_0 = \sigma_f = 0.2$ Nm/rad, plots c and d). Notice in fig.4 that the stiff-and-slow/fast-and-soft paradigm clearly applies to antagonistic actuation.

The minimum time necessary in the two cases is 2.5 s and 2.65 s, respectively. This level of performance should be compared with what can be achieved by a simpler actuation system, consisting of a single actuator connected to the link through a linear elastic element (this arrangement is referred to as SEA, for Series Elastic Actuation [21]). A SEA system with a motor capable of torque $U_{max} = 2U_{1,max} = 15$ Nm and inertia $M_{rot} = 2M_{rot1} = 1.2$ Kgm^2, with linear elasticity coefficient matched exactly with the required stiffness in the two cases $\sigma = 16$ Nm/rad and $\sigma = 0.2$ Nm/rad, would reach the desired configuration in 3.15 s and 3.6 s, respectively.

The general nature of these results was observed to be quite robust with respect to changes in the parameters and the model. For instance, a better model of torque limitation for DC motors could be described by the so-called *speed-torque line* relation,

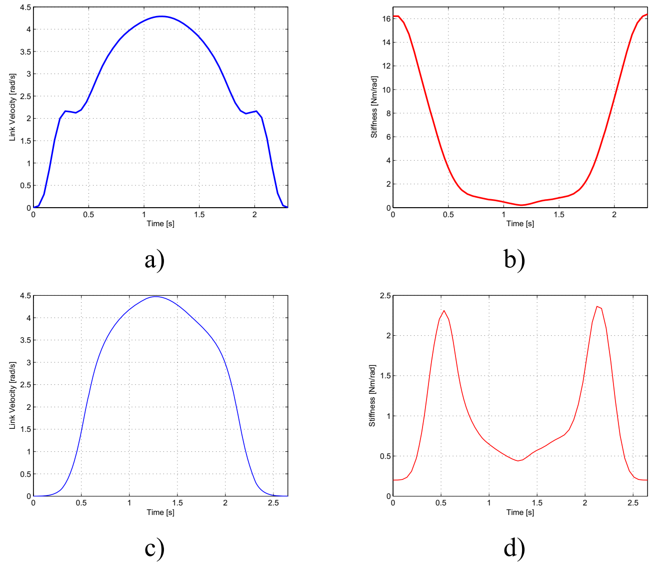


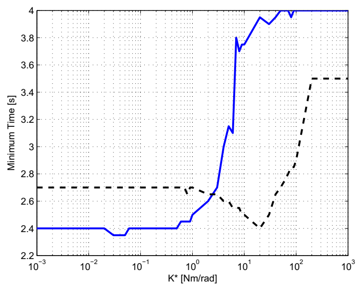
Fig. 4. Optimization results for antagonistic actuation without cross-coupling in a pick-and-place task. A stiff-to-stiff task is shown in a, b, while c, d, refer to a soft-to-soft task.

i.e. $\tau_i \leq \tau_{stall} - \frac{\tau_{stall}}{\dot{x}_{no\,load}}\dot{x}$. Also, a quadratic spring model $\phi_i = K(x_j - x_k)|(x_j - x_k)|$ might be adopted when an overall linear joint compliance is desired. Optimization results in these cases, not shown for brevity, are very similar to what reported for the simpler model above, and still in accordance with the stiff-and-slow/fast-and-soft paradigm.

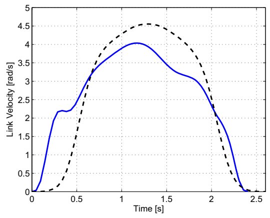
Focusing again on the antagonistic VSA system's results, it is also interesting to notice that, in the likely case that the task requires the manipulator to be stiff at the initial and final configurations (as it would happen e.g. in a precision pick-and-place task), the actuators are required to use a significant portion of their maximum torque just to set such stiffness, by co–contracting the elastic elements. However, it is also in the initial and final phases that torque should be made available for achieving fastest acceleration of the link.

Based on the observation above, it can be conjectured that some level of pre-loading of the non-linear elastic elements in an antagonistic VSA system could be beneficial to performance. Elastic cross-coupling between actuators (fig.3) can have a positive effect in that it can bias the link stiffness at rest, so that more torque is available in slow phases, while torque is used for softening the link in fast motion. On the other hand, it is intuitive that very stiff cross-coupling elements would drastically reduce the capability of the mechanism to vary link stiffness, thus imposing lower velocities for safety, and ultimately a performance loss.

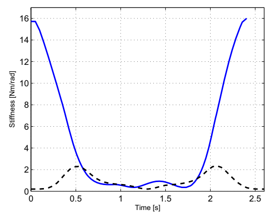
It is therefore interesting to study the effect of cross-coupling, in order to determine if there is an intermediate value of stiffness which enhances performance with respect to the limit cases of no cross-coupling (fig. 1) and rigid cross-coupling (constant stiffness). To this purpose, we study a modified formulation of the safe brachistochrone problem,



a)



b)



c)

Fig. 5. a) Minimum time to reach the target configuration vs. cross-coupling stiffness K_3 ($L_0 = 1$). Solid: $\sigma_0 = \sigma_f = 16$ Nm/rad; dashed: $\sigma_0 = \sigma_f = 0.2$ Nm/rad. Optimization results for antagonistic actuation with cross-coupling in a pick-and-place, stiff-to-stiff task (solid) and soft-to-soft task (dashed): velocity (b) and joint stiffness (c).

namely

$$\begin{cases} \min_\tau \int_0^T 1 \, dt \\ M_{rot1}\ddot{x}_{rot1} + \phi_1(x_{rot1}, x_{mov}) - \phi_3(x_{rot1}, x_{rot2}) = \tau_1 \\ M_{rot2}\ddot{x}_{rot2} + \phi_2(x_{rot2}, x_{mov}) + \phi_3(x_{rot1}, x_{rot2}) = \tau_2 \\ M_{mov}\ddot{x}_{link} - \phi_2(x_{rot2}, x_{mov}) - \phi_1(x_{rot1}, x_{mov}) = 0 \\ |\tau_1| \leq U_{1,max} \\ |\tau_2| \leq U_{2,max} \\ \Sigma(\dot{x}_{mov}, \dot{x}_{rot1}, \dot{x}_{rot2}, \phi_1, \phi_2) \leq \Sigma_{max}, \end{cases} \tag{3}$$

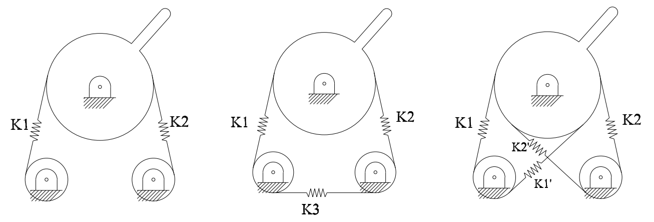
where $\phi_3(x_{rot1}, x_{rot2})$ indicates the cross-coupling elasticity. In particular, we study how optimal solutions vary in different instances of the problem with increasing cross-coupling stiffness. A linear stiffness model is assumed for cross-coupling, with $\phi_3(x_{rot1}, x_{rot2}) = K_3(L_0 + x_{rot2} - x_{rot1})$, where L_0 denotes the pre-load offset.

In fig.5 numerical solutions obtained for problem (3) are reported, for the two tasks (stiff-to-stiff and soft-to-soft) already considered in fig.4. It can be observed from fig.5-a that optimal values of cross-coupling K_3 exist in both cases, but they do not coincide. Setting for instance $K_3 = 0.04$ Nm/rad, the optimal value for the stiff-to-stiff task, we obtain the optimal link velocity and stiffness plots reported in fig.5-b and -c, and the optimal time of 2.35s. It can be observed that, in this case, introduction of the cross-coupling enhances performance by a modest 5%.

III. Antagonistic Actuation Arrangements

In its simplest implementation, an AA arrangement consists of two prime movers connected to the link through two nonlinear elastic elements (see fig. 6-a). Rotations of the motors in the same sense generate a net torque to the joint, while rotations in the opposite sense set different levels of effective compliance at the joint. Depending on the implementation, prime movers can be regarded as either torque or position sources, and elastic transmissions can have different characteristics. We assume that motors have much higher effective inertia at the joint axis than the link itself, due to the fact that in robotic applications high gear ratios are often used (in our analysis, gears are included in the prime-mover element). A laboratory implementation of a simple AA arrangement, using tendons, is depicted in fig. 7-a.

Although simple AA arrangements are probably closest to examples in nature, they might not be optimal for engineering implementation. For instance, in a simple AA with pull-only



(a) (b) (c)

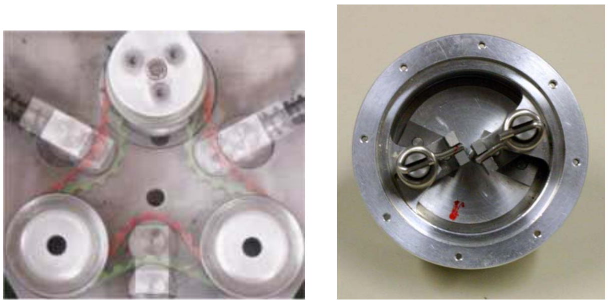
Fig. 6. Three possible arrangements for Antagonistic Actuation: (a) Simple; (b) Cross-coupled; (c) Bi-directional.

(a)

(b)

(c)

Fig. 7. Laboratory prototypes of three AA arrangements: (a) Simple AA with exponential springs; (b) Cross-coupled arrangement of the VSA-I; (c) Bi-directional arrangement of the VSA-II.



(a) (b)

Fig. 8. Implementation details for the cross-coupled AA in VSA-I (a) and the bi-directional AA in VSA-II (b).

Fig. 9. An instrumented proof-mass jig used to experimentally measure impact effects of different VSA arrangements.

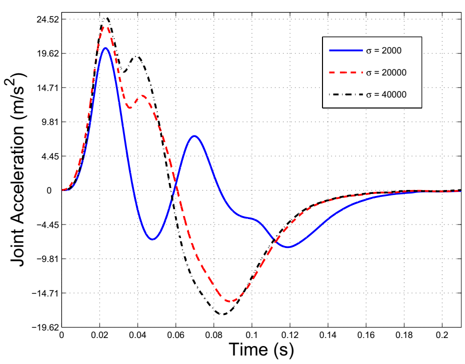


Fig. 10. Accelerations of the probe mass measured after collision with a VSA-powered link vs. time (impacts start at time $t = 0$).

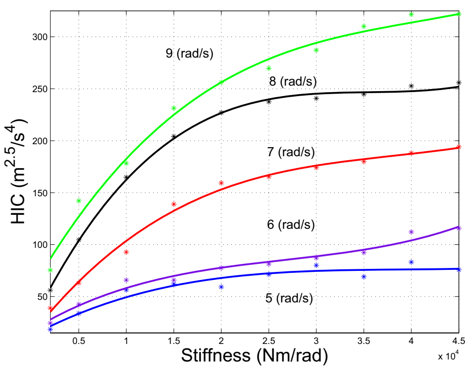


Fig. 11. Experimental evaluation of the HIC index for impacts at different transmission stiffnesses for VSA (dots) and data interpolation by 4th-order polynomial curves (continuous line).

elastic tendons, the maximum torque available at the joint can not be more than that of each single motor, and no net torque is available at the joint when stiffness is at maximum. To overcome these limitations, a possible modification is to introduce a third elastic element (possibly different from the two antagonists) to cross-couple the two prime movers (see fig. 6-b). Cross-coupling allows setting pre-load forces in the system in order to tune it to nominal working conditions, and also allows using (a fraction of) each motor's torque in both directions. The VSA-I prototype introduced in [23] and depicted in fig. 7-b is an implementation of this concept.

One further variation of the basic AA arangements, that addresses the above issues of unidirectional actuation not using cross-coupling, consists in connecting each actuator to the link via two elastic elements (not necessarily symmetric) in push-pull configuration (see fig. 6-c). The VSA-II prototype introduced in [24], and depicted in fig. 7-c implements such a bi-directional AA arrangement. More details on the implementation of the cross-coupled and bi-directional arrangements are visible in fig. 8. In fig. 8-a, two superimposed images of the the VSA-I actuator show differences between stiff (red) and compliant (green) configurations. The link axis is on top, and the cross-coupling nonlinear elastic element is opposite to it, adjacent to the two motor pulleys. Fig. 8-b is a view of one half of the VSA-II mechanism. One motor is connected to the inner pulley (marked in red), while the link is fixed to the outer shells of the two halves. Two elastically pre-loaded four-bar mechanisms are visible, which are used to connect bi-directionally the motor to the outer shell.

The effects of impacts by links actuated with the proposed AA arrangements have been experimentally verified using a laboratory sensorized proof-mass system (fig. 9), providing data that have been useful to iteratively tune the optimization parameters. As an example, results reported in fig. 10 illustrate the different measured accelerations of the probe after impacts corresponding to different values of stiffness. The effect of lower stiffness in reducing the maximum acceleration are evident. To further investigate the influence of transmission stiffness on safety, measurements were taken at different values of stiffness and different impact velocities. In these experiments, stiffness and velocity were set to constant values before impact. The corresponding values of HIC are reported in fig.11. These data show that the adverse effect of transmission stiffness on safety is saturated for stiffness values above a limit, which however increases with the link velocity. Planning strategies can be based on such data to guarantee sufficient compliance at different velocities, so as to maintain a constant worst-case HIC value. Experimental

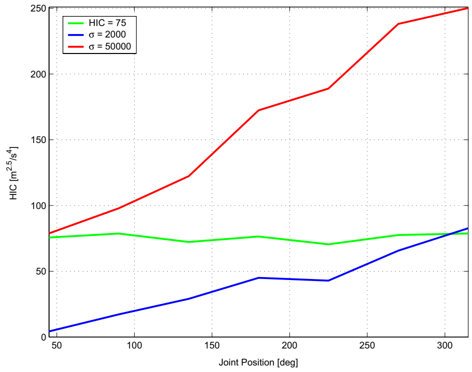


Fig. 12. HIC of impacts experimentally measured in tests with the VSA prototype. Solid line (green): stiffness controlled according to the hybrid motion/stiffness planning method described in the text. Dashed (blue) and dash-dot (red): constant stiffness $\sigma = \sigma_{min} = 2\,10^3$Nm/rad and $\sigma = \sigma_{max} = 5\,10^4$Nm/rad, respectively.

results obtained by such a hybrid motion/stiffness planner on the VSA prototype are reported in fig. 12. A number of impact tests were conducted, with impacts occurring at different velocities of the joint during the acceleration phase. It can be noticed that implementation of the hybrid motion/stiffness planning method results in experimental HIC indices very close to the set value (HIC = 75 $m^{2.5}/s^4$): the maximum error is below 5.5%. HIC values obtained with constant stiffness are also shown for reference.

IV. Conclusions

Few different arrangements of 1-dof link-joint antagonistic actuation mechanism for pHRI applications have been considered. Several aspects like performance, safety and dependability should be considered in order to get a comprehensive picture for the comparative analysis of the various alternatives.

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