Mechanical Design-based Solutions for Safe Physical Human–Robot Interactions: Joint Compliance vs. Link Compliance*

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I. Introduction

In recent years, increasing interest of researchers has been drawn to the collaborative robots or co-robots, which are intentionally designed for physical interactions with human beings. Co-robots have been widely used in variable applications, including automotive industries [1], surgical assistance [2], homes/offices service [3], and so on. Unlike traditional industrial robots that are kept separated from humans to ensure safety, co-robots are designed to physically interact with humans in a shared workspace. However, safety has been a major concern that limits their applications.

Typical solutions to address safety concerns may include the sensor-based approach and mechanical design-based method. The former is widely used and it may rely heavily on a fully equipped and sensorized computer environment. The latter, as a complementary solution, can offer an guaranteed inherent safety for physical human-robot interaction (pHRI), which is the focus of this study. Joint compliance and link compliance are two typical representatives to introduce mechanical compliance to robots. Extensive research has been conducted on the joint compliance, including serial elastic actuator (SEA)[4], variable stiffness actuator (VSA)[5], [6] or variable stiffness joint (VSJ)[7], [8], [9]. Recently, researchers started to investigate the link compliance, including safe link mechanism [10], [11], [12] and variable stiffness link (VSL)[13], [14], [15], [16].

To evaluate the safety effectiveness of pHRI systems with joint compliance or link compliance, we must specify a safety criterion. In this study, we consider the impact force as the evaluation indicator.

Since both VSJ and VSL can be used to address inherent safety for pHRI, it is critical to compare their performance for designing pHRI systems The goal of this work is to evaluate the effectiveness of mechanical compliance to enhance safety in pHRI. The specific scientific questions to be answered in this research are: (1) How do design parameters (mass, mass ratio and mechanical stiffness) and actuation parameters affect the maximum force during a pHRI? (2)How effective is varying mechanical compliance to reduce the impact force? (3) Which design is more effective in reducing the maximum impact force, compliant link or compliant joint?

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II. Method

In order to systematically evaluate the safety effect of mechanical compliance, we develop theoretical models of a pHRI system including contact force model, robot dynamics, and dummy head dynamics.

We leverage the piecewise Hertz contact model [17] in this study to estimate the impact force. We implemented the Euler-Lagrange approach method to model the dummy head dynamics as well as the robot dynamics with rigid links and compliant joints. We utilized the assumed modes method (AMM) [18] to model the robot dynamics with compliant links and rigid joints.

To validate the theoretical models, we established a platform for simulating the impact process of a pHRI system with compliant joint (CJ) or compliant link (CL) in MATLAB Simscape. It is observed that the numerical results of the theoretical models agree with those of the MATLAB Simscape models for both of the CJ and CL design.

III. Results

In this section, we present a comprehensive comparison of joint compliance and link compliance in pHRI. Note, a VSL can be obtained if we consider a range of stiffness values of the CL design. Similarly, a VSJ can be achieved if we give a range of stiffness value of the CJ design.

Given equivalent parameters of the VSJ and VSL design, we study the free impact of the pHRI system, i.e., $\tau_m = 0$ (τ_m is the motor torque), and have the following observations: (1) The effects of the joint stiffness on the maximum impact force for the VSJ are negligible because the joint spring has decoupled the motor and link inertia by the intrinsic joint elasticity. Changing stiffness will have minor effects on $F_{\max}$ (the maximum impact force) if other parameters hold unchanged. This result well agrees with the experiment testing with KUKA robots reported in [19] and MIT Cheetah in [20]. (2) In contrast, $F_{\max}$ of the VSL is considerably affected by the stiffness of the compliant link even if there are no external torques applied to the motor. For instance, R_{f} (the maximum impact force reduction) of the VSL can be up to 57.1% at v_0 = 3 m/s (v_0 represents the initial impact velocity). The observation indicates that reducing the stiffness of the compliant link may effectively lower $F_{\max}$ of the VSL. (3) In general, VSJ designs produce a larger $F_{\max}$ than VSL designs for each impact velocity. When the lateral stiffness is small (compliant arms), this difference is quite noticeable. However, as the lateral stiffness increases, there is no difference between these two designs. This is because both designs can be regarded as equivalent to the case of a rigid link with a rigid pin joint. The observation is held true for various impact velocities.

Second, we study the case of a constant motor torque applied during the impact process, i.e., $\tau_m \neq 0$. In addition to those observations listed above, two new findings are summarized in the following: (1) The profile of $F_{\max}$ is close to a sigmoid function for both the VSJ and VSL designs. In other words, $F_{\max}$ has a sharp "step" change given a certain range of lateral stiffness variation but it is saturated from both sides. (2) While the VSJ has a slight variation of $F_{\max}$, the magnitude of variation is much smaller than that of the VSL. For instance, R_{f} of the VSJ is increased by 4.2% if a constant torque of 5 N.m is applied by the motor. However, the maximum impact force reduction ratio R_{f} of the VSJ is as high as 39.2% given the same parameters.

It is worth noting that the variation of $F_{\max}$ is prominent merely at a certain range of lateral stiffness. In other words, changing the lateral stiffness may not necessarily reduce/increase $F_{\max}$ if the stiffness variation is out of the critical range. The prominent variation of $F_{\max}$ depends on not only the variation of the lateral stiffness, but also on its critical range. This is important for engineers in the design process and will be explored later in more details.

Next, we take a look at effects of mass property parameters under free impact. Here, we define the mass ratio R_m as $R_{\mathrm{m}} = \frac{m_{\mathrm{r}}}{m_{\mathrm{e}}}$, where m_{r} and m_{e} are the mass of the robot arm and end-effector respectively. In addition to the similar trends as mentioned previously, two other findings are summarized in the following: (1) Without motor torques, the effect of k_{l} (effective lateral stiffness) on $F_{\max}$ can be almost neglected for the VSJ given various sets of design parameters of R_{m} and m_{e}. However, $F_{\max}$ of the VSL is noticeably affected by k_{l}. (2) Larger R_{m} or m_{e} produces larger $F_{\max}$ for both the VSJ and VSL. This well agrees with our intuition because larger R_{m} or m_{e} generates larger equivalent kinetic energy resulting larger impact force at the end effector, given all other parameters the same.

By comparing the performance of the CJ and CL designs, we observed that the link compliance has a better performance in terms of reducing $F_{\max}$ for pHRI. We summarized the advantages of the CL design in the following: (1) The CL design generally produces a smaller $F_{\max}$ compared to that of the CJ design, given the same parameters and lateral stiffness. When lateral stiffness is very large (close to rigid link), there is no difference between CJ and CL designs in terms of maximum impact force. This implies that CL designs are always better than or the same as CJ designs. (2) Without a motor torque, i.e. free impact, $F_{\max}$ is negligibly affected by k_{l} for the VSJ, but it is considerably affected by k_{l} for the VSL with the same other parameters. The observation holds true for various v_0, R_{m} and m_{e}. (3) With active motor torques, R_{f} of the VSJ is considerable smaller than that of the VSL.

With those observations, we believe it is possible to effectively reduce $F_{\max}$ by reducing k_{l} for the CL design, no matter whether there is motor torque or not.

Note that we also found the CL design permits a higher bandwidth compared with the CJ design [14]. Therefore, in addition to the benefits of the impact force reduction, the CL design may permit a quicker time response with a smaller settling time than that of the CJ design.

It is worth mentioning that the method may not apply to highly dynamic systems or heavy inertia robots where the impact velocity and inertia are dominated factors to affect the magnitude of the impact force.

IV. Conclusions

This work studies the effects of mechanical compliance on safety of physical Human-Robot Interaction (pHRI). More specifically, we compare the effect of joint compliance and link compliance on the impact force assuming a contact occurred between a robot and a human head. We establish pHRI system models that are comprised of robot dynamics, an impact contact model, and head dynamics. These models are validated by Simscape simulation.

By comparing impact results with a robotic arm made of a compliant link (CL) and compliant joint (CJ), we conclude that the CL design produces a smaller maximum impact force given the same lateral stiffness as well as other physical and geometric parameters. In addition, we compare the variable stiffness joint (VSJ) with the variable stiffness link (VSL) for various actuation parameters and design parameters. While decreasing stiffness of CJs cannot effectively reduce the maximum impact force, CL design is more effective in reducing impact force by varying the link stiffness. Furthermore, tuning the stiffness of joints or links may not necessarily reduce/increase the maximum impact force if the stiffness variation is not within a certain range.

More detailed findings are summarized in the following. Given equivalent lateral stiffness and mass properties parameters, CL designs generally outperform CJ designs in the sense of reducing the maximum impact force. For the case study in the article, the maximum impact force of the CL design is 12.9% less than the CJ design. While the maximum impact force reduction is limited for the CJ design, especially without a motor torque, it is prominent for the CL design. For instance, the CJ design leads to a maximum impact force reduction of 4.2% while the CL design reaches a maximum impact force reduction of 39.2% given the same parameters with an active motor torque of 5 Nm. For the case of free impact (zero motor torque), the CJ design barely achieves impact force reduction due to the decoupling effects, while the CL design can still reduce the maximum impact force by up to 57.1%. The results indicate that the CL design has the potential to reduce the maximum impact force more effectively. This study theoretically demonstrates that the CL design can be a promising alternative approach and potentially outperforms the CJ designs in addressing safety in pHRI.

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