ABSTRACT
Due to the limited control bandwidth of pneumatic artificial muscles, joint stiffness characteristics and their effects on safety and performance of human-friendly robots should be considered in the frequency domain. This paper introduces the concept of effective dynamic stiffness and validates its model with the Stanford Safety Robot. Experimental results show that the dynamic stiffness demonstrates limited effects on the impact acceleration given the same impact velocity and controller gain, whereas it significantly affects control performance of position tracking due to pressure-induced non-linearities. A stiffness optimization strategy for safety and performance is discussed as a design guideline of human-friendly robots.

Keywords: stiffness; human-friendly robot; pneumatic artificial muscle.

LES EFFETS DE LA RIGIDITÉ DYNAMIQUE SUR LA SÉCURITÉ ET LA PERFORMANCE DES ROBOTS DANS UN ENVIRONNEMENT HUMAIN

RÉSUMÉ
À cause des limites sur le contrôle de la bande passante des muscles pneumatiques artificiels, les caractéristiques de rigidité des joints, et leurs effets sur la sécurité et la performance des robots dans un environnement humain devraient être considérés dans le domaine des fréquences. Cet article introduit le concept de rigidité dynamique effective, et son modèle est certifié auprès de la Stanford Safety Robot. Les effets potentiels de la rigidité dynamique sur la sécurité et la performance sont investiguées au moyen de comparaisons expérimentales des accélérations de choc, et le suivi de la position sinusoidale, respectivement. Les résultats des expériences montrent que la rigidité a des effets limités sur l’accélération de choc étant donné le même impact sur la vitesse de choc et sur la commande de gain, où les effets affectent significativement le contrôle de la performance des non-linéarités induites par la forte pression.

Mots-clés : rigidité ; robot dans un environnement humain ; muscle pneumatique artificiel.
1. INTRODUCTION

Recently, numerous robotic platforms are being created in environments where close interactions with humans are essential. Therefore, robot manipulators must be safe enough in human proximity to make humans feel comfortable. ISO 10218-1 was developed in order to reduce the chance of human injury [1]; however, these regulations interfere with the potential for achieving fast motion in robots. For safe human-robot interaction, researchers have been developing robots whose open-loop characteristics are sufficiently safe to human collaborators no matter what system malfunctions and user mistakes occur.

One of the most promising methods for robot safety is inertia reduction. For a given joint velocity, low-inertia robots are less likely to cause injury. Configurations using direct drive electromagnetic motors [2] or relocating motors to the base using cables [3] generate less actuator or link inertia, respectively. DLR’s LWR III employed a light structure mechanism [4] with Joint Torque Control (JTC), which allows for near zero output impedance at low frequencies [5].

Pneumatic Artificial Muscles (PAMs) provide high force-to-weight ratio, which allows for low inertia actuation and link design. PAMs have the potential to serve as safe actuators by reducing effective inertia and consequently decrease impact forces. However, PAMs’ nonlinear behavior and low dynamic ranges have prevented them from widely being employed in practical applications. Addressing this issue, Shin et al. [6] developed a hybrid actuation approach combining PAMs and high bandwidth electric motor in parallel, which compensates for low performance of PAMs without compromising robot safety. Figure 1 shows the new design of the Stanford Safety Robot (S2ρ) with hybrid actuation.

On the other hand, achieving low joint stiffness seems another popular method for robot safety. Low stiffness is believed to decrease impact force, but provides poor position control performance. This trade-off has led many researchers to investigate variable stiffness actuations in order to achieve apparent competing objectives, robot safety and performance [9, 10]. However, joint stiffness has been shown to have little effect on HIC (Head Injury Criteria) collision values [11] and very limited effect on impact force [12].

Since limited position and force control bandwidth render joint stiffness frequency-variant, these stiffness characteristics and their effects on robot safety and performance should be investigated. Understanding how
stiffness alters with frequency-variations will allow for improvements on controller and mechanism designs. Section 2 presents an effective dynamic stiffness model describing how stiffness varies with frequency. Section 3 describes an experimental setup in the Stanford Safety Robot (S2ρ) testbed to evaluate dynamic joint stiffness and inertia effects on robot safety and performance [6]. Section 4 provides experimental validation of the effective dynamic stiffness model, and analysis of the stiffness effects on impact acceleration and position tracking. Finally, Section 5 discusses a strategy to obtain optimal stiffness based on the result analysis.

2. DYNAMIC STIFFNESS MODEL

In order to properly evaluate stiffness effects on robot performance along with robot safety, Shin developed an effective dynamic stiffness model combining an inherent stiffness generated by PAMs and active stiffness produced by a controller in the frequency domain [13]. Our stiffness model further characterizes how a joint behaves when an actuator and/or a controller affect dynamic joint stiffness. In order to derive the effective dynamic stiffness, the impedance of a pneumatic-muscles-driven joint is first derived as follows:

\[
\frac{\tau_{\text{ext}}(s)}{\dot{\theta}(s)} = I_{\text{eff}}s + B + \left\{ k_m + \frac{k_{pp}E}{s+k_{pp}E}(k_p - k_m) \right\} / s,
\]

\[
k_m = \frac{P_0b^2}{4\pi n^2} \left( \frac{6L_0}{b^2} \right) \left( \frac{3L_0^2}{b^2} - 1 \right),
\]

\[
E = \frac{b^2 k_{\text{valve}}}{4\pi n^2} \left( \frac{3L_0^2}{b^2} - 1 \right),
\]

where \( k_m, k_p, \) and \( k_{pp} \) are passive joint stiffness by antagonistic pair of muscles, position controller gain, and force controller gain, respectively. \( B \) is damping coefficient, \( P_0 \) is initial muscle pressure, \( L_0 \) is initial muscle length, and \( R \) is pulley radius. \( E \) is PAM property including \( k_{\text{valve}} \), which is empirically obtained valve gain. \( b \) and \( n \) are muscle constants [14] (see [13] for the detailed equations). From Eq. (1), the joint
**3. EXPERIMENTAL SETUP**

We employed the S2ρ testbed [6] in order to validate the dynamic stiffness model and its effect on robot safety and performance. In the first experiment, we validated the effective dynamic stiffness model by moving the arm from rest with various $k_m$ and $k_{pp}$. The attached mini electrical motor in the S2ρ testbed generated the step external torque input. The effective dynamic stiffness is identified by the following equation:

$$k_{eq} = k_m + \frac{k_{pp}E}{s + k_{pp}E} (k_p - k_m),$$

where the external joint torque, $\tau_{ext}$, and the joint angle, $\theta$, are measured by the load cell and the joint encoder, respectively.

We also used the S2ρ robotic arm for impact forces as measured against a steel disk target covered in compressible foam as shown in Fig. 2. The steel disk matches median mass (6 kg) of a male head and neck [15] while the compressible form simulates head stiffness ($k_{int} = 37$ kN/m). The disk was outfitted
with an accelerometer to measure impact acceleration. The robotic arm was mounted such that the motion was perpendicular to gravity, minimizing the effect of gravity on collision dynamics.

4. EXPERIMENTAL RESULTS

4.1. Identification of Dynamic Stiffness

As reported in [13], dynamic stiffness diminishes as impact frequency increases. Figure 3a shows that the dynamic joint stiffness is proportional to $k_m$ initially, then quickly decreases to zero as a force controller compensates for force error. Note that the system was under force control but not position control ($k_p = 0$). The nonzero steady-state stiffness for high $k_m$ is caused by hysteresis due to high pressure. We observed that limited force control bandwidth results in an instantaneous increase in dynamic stiffness, and the higher performance controller decreased the stiffness faster by eliminating force error, as is shown in Fig. 3b [13].
Figures 3c–d show the effective dynamic stiffness in the frequency domain [13]. At a low frequency, the stiffness converges to zero due to the joint torque control. However, the stiffness approaches $k_m$ at a high frequency due to the control bandwidth limitation. Figure 3d shows that a higher controller gain further decreases the stiffness at a low frequency, while at a high frequency the stiffness eventually converges to $k_m$ independent of controller gain [13].

4.2. Dynamic Stiffness Effects on Safety
We measured impact acceleration as a metric of robot safety with respect to the joint stiffness produced by PAMs and the force controller gain of PAMs. For each experiment, the manipulator velocity was controlled through the impact location. As shown in Fig. 4a, the impact acceleration is almost independent of the joint stiffness at the impact velocities of 0.4 m/s. Higher $k_m$ appears to increase the impact acceleration at the impact velocities greater than 0.4 m/s, however the difference in value is not significant. Figure 4b shows that higher $k_{pp}$ effectively reduces impact acceleration, but at a high velocity of 2.0 m/s, the difference is marginal.

As the impact velocity increases, inertia is further critical to the impact force than joint stiffness and force controller gain. Even high $k_m$ has a marginal effect on the impact acceleration due to the lower impact duration at a high impact velocity. Furthermore, relatively lower joint stiffness than interface stiffness seems to decouple the inertia of the previous links and actuator from the end-effector. Figure 5 shows that inertia of the last link is the dominant contributor to the impact acceleration at a high impact velocity while stiffness has minimal effects on it.

4.3. Dynamic Stiffness Effects on Performance
As reported in the previous section, dynamic stiffness effects on robot safety is limited. However, the stiffness significantly affects robot performance. While higher effective joint stiffness is typically advantageous for controllability, force control limitation of PAMs instantaneously increases effective dynamic stiffness at transient phases, and thus results in interference, particularly in the hybrid actuation [16].
As shown in Eq. (2), controller-based stiffness, $k_p$, is dominant at low frequencies, where the bandwidths of most position controllers lie. Thus, designing $k_p$ is sufficient to obtain desired position control performance.

However, at high frequencies, inherent stiffness by PAMs, $k_m$, plays key roles for contact control and disturbance rejection due to bandwidth limitation of position controller. For better contract control, passive compliance, i.e., low $k_m$, may be desirable, but excessive compliance results in difficulties in position control. On the other hand, in order to enhance disturbance rejection, actuator needs to employ high $k_m$, which accordingly increases effective dynamic stiffness at high frequencies, and thus interference particularly in the hybrid actuation.

In order to evaluate how effective joint stiffness affects control performance, we conducted position tracking experiments. Figure 6 shows that (a) lower $k_m$ for the desired 4 Hz position tracking results in oscillations, while (c) the control performance of hybrid actuation suffers from excessively high $k_m$, which increases non-linearities and interferences between PAMs and electrical motors [16]. Meanwhile, (b) optimal stiffness provides better controller performance while minimizing oscillations and interferences.

5. CONCLUSIONS AND DISCUSSION

Simulation and experimental results with the Stanford Safety Robot show that the stiffness demonstrates limited effects on the impact acceleration given the same impact velocity and controller gain, whereas it significantly affects control performance due to pressure-induced non-linearities. The effect of stiffness on robot safety is marginal in particular at a high impact velocity since effective inertia and interface stiffness dominantly influence impact force. While the rule of thumb is higher joint stiffness for controllability, non-linearities and interferences cancel out the advantages of higher stiffness, particularly in PAMs-driven systems.

Our results demonstrate that it is possible to decouple robot performance from robot safety when it comes to determining the inherent stiffness by PAMs and control gain. In other words, we can choose these parameters mainly for robot performance since the effects of these parameters on robot safety are limited to low velocity impacts, in which safety is mostly not a critical issue.
We have developed a strategy to obtain optimal dynamic stiffness for better control performance. The optimal strategy employs appropriate evaluation functions such as impedance, elastodynamics, and energy efficiency. We are also investigating a novel transmission and its control algorithm in order to mitigate dynamic stiffness instantaneously increased by the bandwidth limitation of PAM’s position and force controller.

Incorporation of an appropriate friction model of PAMs into the effective dynamic stiffness model will allow for less deviation of the experimental data from the model particularly at high muscle stiffness. High muscle stiffness typically requires high muscle pressure, which increases muscle internal friction and damping nonlinearly.

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