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Examining The Benefits of Variable Impedance Actuation

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Abstract— **Variable impedance actuators provide the ability to robustly alter interaction impedances mechanically, without bandwidth, power, and stability limitations. They can achieve the physical benefits of an elastic transmission and also recover characteristics of traditionally controlled, inelastic motors. We review previously explored benefits of variable impedance actuators for energetic tasks and impact safety. We then focus on benefits in low frequency force interactions. We examine impedance and force dynamic ranges and illustrate how they are significantly increased by physical impedance variation. Theoretical analysis is confirmed by experiments on a 1-DOF testbed with three impedance settings.**

I. Introduction

Robots are increasingly being asked to perform human-like tasks in human-centric environments. Properties such as safety and efficiency are beginning to be prioritized over precision and repeatability. Stiff actuators, such as geared DC motors or hydraulics, are being replaced with series elastic or compliant designs.

More recently, variable impedance actuation has been advocated for its ability to adjust the transmission elasticity. In this work, we review the known benefits of variable impedance actuation, for instance, regarding safety, locomotion, energy storage and efficiency. We then focus attention on the benefits of variable impedance for basic, low-frequency force interaction tasks. In particular, we examine the dynamic range of achievable impedances and forces. A large dynamic range allows a robot to perform a greater range of interactions, executing heavy tasks and delicately handling light objects. We validate our theoretical developments using a single degree of freedom actuator with adjustable impedance settings. We find that a physically variable impedance provides superior performance to basic fixed-impedance configurations, matching and potentially exceeding the range exhibited by traditional inelastic actuators.

II. Background

A. Actuator Properties

In Table I we show the properties of actuator types commonly used in robotics. These properties include the ability to perform energetic tasks such as running, where large amounts of power are cyclically transfered to and from the actuator or throwing, where large peak power is desired.

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We also list actuator safety, for humans or for delicate environments, which is primarily determined by impact forces. Impacts contain high frequency content, and are thus shaped by the high frequency impedance of the actuator, which is dominated by inertial effects. For manipulation capabilities we look at low frequency force interactions, which are determined by the low frequency actuator impedance, dominated by intrinsic stiffness, damping, and any control laws used to program a desired impedance. Finally, we give the actuator bandwidths in velocity and force regulation.

B. Actuator Types

At one extreme of actuator types, robots have been built with direct drive or limited gearing, highly backdrivable actuators to facilitate clean dynamic performance and high bandwidth. These actuators approximate pure force sources with limited mass and friction, making them intrinsically safe during impacts. However, their limited gearing also implies limited power and maximum forces, so that they are not applicable to energetic or heavy tasks, and cannot reject large disturbances. Properties of ungeared actuators are summarized in the first column of Table I.

At the other extreme, robots are often built for accurate positioning, large forces, and disturbance rejection. This requires stiff interfaces and is often achieved through a large gearing. These high mass interfaces result in dangerous impact forces during collisions, and are more capable of functioning as position sources than force sources. Attempting to use feedback control to make the actuator feel lighter or more compliant can result in non-passive or unstable systems and cannot be implemented beyond the controller bandwidth. These characteristics associated with highly geared actuators are summarized in the second column of Table I.

Alternatively, robotics engineers have purposefully introduced compliance into the actuator transmission path, trading some bandwidth in order to overcome some of the limitations of highly geared actuators while retaining their large force capabilities and power density. In their work on Series Elastic Actuators (SEAs), researchers introduced a spring in series with the actuator, suggesting that the elasticity would lower impact forces, change force control into a position control scheme, stabilize force control during contacts, provide energy storage, provide a high fidelity force source, and increase peak power output over traditional motors[1], [2], [3]. These attributes make compliant actuators attractive choices for applications in human safe robotics[4], legged locomotion[5], and for performing quick motions such as throwing, hopping and swinging[3]. Recent work expanding on SEAs has focused on restoring some of the bandwidth

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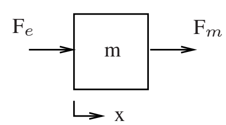
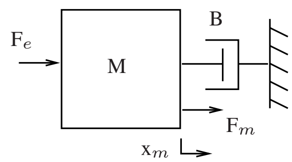
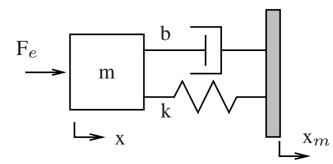
	Ungeared Actuator	Highly Geared Actuator ⟵ Variable	Impedance ⟶ Series Elastic Actuator
Energetic Task Capabilities	no energy storage ability low peak power	no energy storage ability low peak power	energy storage ability high peak power
Actuator Safety Properties	low mass low impact forces	high mass high impact forces	low output mass low impact forces
Low Frequency Force Properties	low maximum force low friction	high maximum force high friction	high maximum force low friction
Force & Velocity Bandwidths	high velocity bandwidth high force bandwidth	medium velocity bandwidth medium force bandwidth	low velocity bandwidth low force bandwidth
Model			

TABLE I
SUMMARY OF ACTUATOR TYPES, CAPABILITIES, AND BASIC MODELS

lost in incorporating compliance into human safe robots via elastic components[4] and pneumatic muscle[6]. The properties of SEAs and other compliant actuators are shown in the third column of Table I. While series compliance has proven to be extremely useful, the manufacture of a compliant actuator requires the designer to trade-off between bandwidth, safety, and stability or to select gait, hopping or throwing parameters up front and then accept the actuator's characteristics permanently.

Variable impedance actuators allow a robotic interface to vary between stiff and compliant. Their ability to provide low impedance grants them the same abilities associated with compliant actuators such as SEAs. However, the designer does not have to accept an invariable tradeoff between a stiff and compliant interface, or permanently select natural dynamics. When necessary, the actuator can be stiffer, resembling a geared actuator with higher position accuracy, higher bandwidth, and faster dynamics. This provides variable impedance actuators with additional benefits over compliant interfaces, summarized in Table I by the ability to change between an SEA and a highly geared actuator.

C. Impedance Control and Dynamic Range

A robot and its actuators can be described by the impedance they present to the environment. This impedance is often viewed from the low and high frequency perspectives. The low frequency impedance determines the slow and steady state behavior, including the apparent stiffness and damping. When placed under software control, position and force feedback are used to program the impedance as appropriate for the task at hand.

The high frequency impedance determines forces during short duration events, such as impacts. Since feedback control is inherently of limited bandwidth, it does not change the high frequency impedance. Thus this impedance range is dominated by the actuator's output mass, and unaffected by control.

The actuator's overall impedance dynamic range captures the level of the robot's programmability. While feedback control effects are limited to low frequency impedance, physical variations can affect impedance over the entire frequency spectrum. Thus both hardware alterations and software control can be used, over their corresponding frequency ranges, to set the output impedance.

III. DEMONSTRATED BENEFITS OF VARIABLE IMPEDANCE

Variable impedance actuators, such as the general designs described in [7], [8], offer several advantages over both stiff and compliant robotic interfaces. These advantages include higher performance during safe actuation, higher range of task capabilities, ability to implement impedance control despite controller bandwidth limitations, simpler telerobotic strategies, better physical human-robot interaction (pHRI), tunable dynamics for walking and running, tunable dynamics for throwing and swinging, and energy efficient movement. The following benefits have been previously discussed in the literature.

1) Higher Safety and Performance, More Effective pHRI: Safe robots often use some form of compliance to decouple actuator inertia from the end effector, reducing impact forces. If this coupling can vary, the robot can be compliant while in motion, and stiff during initial acceleration or during positioning. Researchers have suggested that, given a safety constraint, a variable stiffness actuator will have higher performance than either SEA or Macro-Mini[4], [6] actuation and that the performance gain increases with the range of achievable stiffnesses[9]. The strategy proposed in this work has been implemented using a variable damper/brake [10]. [11] concluded that human-robot cooperation was improved for moving and positioning tasks by implementing variable damping in software gains. [12] used coupling and decoupling of reflected rotor inertia to alter the high-frequency impedance of the device and influence impact force magnitude.

2) Better Automatic and Teleoperated Task Completion: When a situation requires a range of tasks to be completed, either automatically or telerobotically, variable impedance is a tool for handling the range of interactions. [13] noted that programmable compliance is required for assembly tasks and that each task will have its own suitable compliance. In bilateral teleoperation, [14] found that changing the slave impedance affected the user's ability to remotely push a switch.[15] found that allowing telerobotic damping gains to vary improved telerobotic tracking performance. [16] showed that a variable impedance slave device allows the user to adopt simpler and more intuitive strategies in controlling the robot.

3) Overcoming Controller Limitations in Implementing Programmable Compliance: Programmed compliance is needed in several applications, from part assembly to manipulation. Traditionally this compliance has been implemented via force feedback, although bandwidth limits and instability make this difficult. [7] argues that mechanical components should be used to implement programmable impedance due to the contact instability of force feedback loops and the low energy efficiency of direct drive systems. [17] developed a variable impedance finger joint for use in dexterous manipulation, motivated by the inability of active force control to provide a high level of compliance or deal with multi-point contact. [18] developed an ER damper with variable damping in order to minimize structural resonances in robotic arms for precise control of non-colocated end effector position.

4) Controllable Gaits in Legged Locomotion: Physical compliance is a useful attribute of legged locomotion due to its ability to reduce impact forces and store energy during the gait. [19] implemented variable compliance into a robotic leg to overcome motor bandwidth limits and improve the robustness of running.

The dynamics of limit cycles found in robotic locomotion are dependent on the compliance of the mechanical components. Variable impedance actuators grant the ability to adjust these gait dynamics in realtime instead of tuning them during the design phase. [20], [19] noted that varying stiffness controls the speed of walking and running and that humans and animals employ this control strategy. Several researchers have studied and implemented variable compliance in order to control gait dynamics for energy efficient walking and running at different speeds and on different surfaces[21], [22], [23], [24], [25], [26].

5) More Efficient Energy Usage for Movement, Throwing, Walking, Hopping and Swinging: The ability of compliant actuators to store and release energy allows them to achieve higher peak power than a motor alone. This is useful for energetic tasks requiring short bursts of power. Variable compliance allows this energy storage and release to be tuned to the task at hand. [27] built a robotic shoulder with variable impedance in order to implement the optimum stiffness for throwing, which changes with the object thrown. [28] used a variable impedance actuator to show that swing velocity can be controlled through stiffness. [29] showed that varying the joint natural frequency through changing compliance reduces the energy consumption and control effort needed during movement.

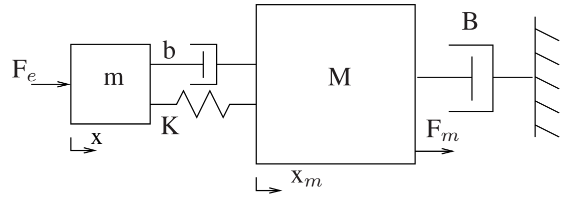


Fig. 1. Inelastic Actuator Model with Structural Compliance

IV. Low Frequency Impedance and Force

In Table I we saw how the various actuator types provide different benefits with respect to energetic tasks, safety, low frequency capabilities and bandwidth. Here we focus on the low frequency performance and, in particular, try to understand the impedance and force dynamic ranges of the actuator types. We examine the maximum achievable low frequency impedance and force as well as the smallest controllable force levels. We show that fixed actuation types provide a limited dynamic range while variable impedance actuation opens the possibility to drastically increase dynamic range.

A. Impedance Dynamic Range of Inelastic Actuators

We first consider the rigid, presumably geared actuator. The simplest model, as in Table I, describes it as a large mass with large friction and equations of motion,

$$M\ddot{x}_m + B\dot{x}_m = F_m + F_e \tag{1}$$

We lock the motor with a P.D. position controller

$$F_m = -k_p x_m - k_d \dot{x}_m \tag{2}$$

With x and x_m equivalent in this model, we achieve the largest possible impedance visible to the environment,

$$\frac{F_e}{V} = Ms + (B + k_d) + \frac{k_p}{s} \tag{3}$$

For low frequencies, the spring term dominates and the highest impedance is a stiffness

$$Z_{LF,max} = \frac{k_p}{s} \tag{4}$$

If we expand the model to include structural compliance, as modeled in Figure 1, the elasticity in series with the P.D. reduces the maximum low frequency impedance to

$$Z_{LF,max} = \frac{1}{s}\frac{k_p K}{k_p + K} \tag{5}$$

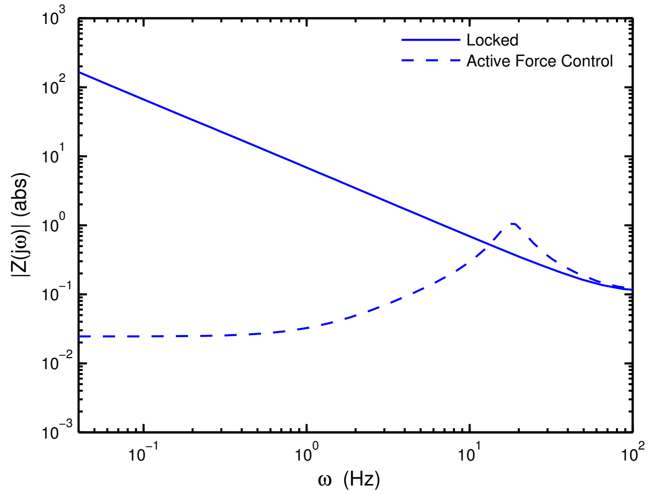


Fig. 2. Theoretical Minimum and Maximum Low Frequency Impedances for an Inelastic Actuator

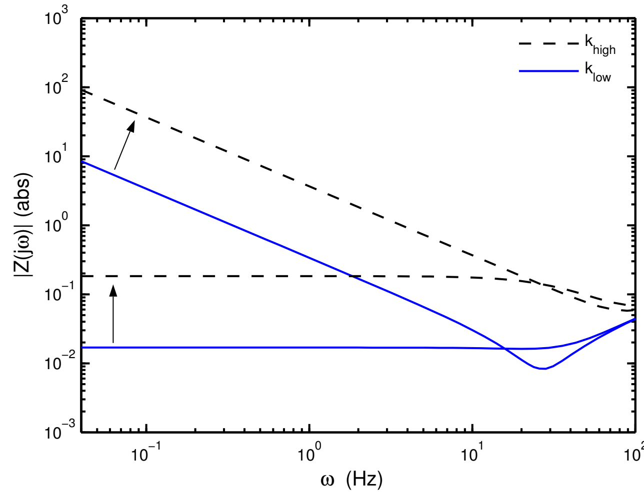


Fig. 3. Theoretical Minimum and Maximum Low Frequency Impedances for Two SEAs with Low and High Stiffness

Regardless of the presence of structural compliance, the lowest impedance and forces are generated by zeroing the actuator ($F_m = 0$) or using active force control ($F_m = k_f F_e$). The latter gives a low frequency impedance equal to the reduced actuator friction

$$Z_{LF,min} = \frac{B}{1 + k_f} \tag{6}$$

If we consider the structural compliances modeled in Figure 1 as before, we note that their presence will limit any force control gain k_f. Using this model, Figure 2 graphs the minimum and maximum impedance when force controlled and locked, respectively, using parameter values consistent with the experimental hardware described below.

We also note that increases in the actuator's gear ratio will raise the apparent position gain k_p as well as the perceived actuator friction B. So while force and impedance levels will rise, their dynamic range remains constant.

B. Impedance Dynamic Range of SEAs

In a series elastic actuator, as shown in Table I, the motor is isolated from the environment behind a compliance

$$m\ddot{x} + b\dot{x} + kx = F_e + b\dot{x}_m + kx_m \tag{7}$$

We consider the motor to be non-backdrivable and position controlled to x_d

$$M\ddot{x}_m + B\dot{x}_m = k_p(x_d - x_m) - k_d\dot{x}_m \tag{8}$$

which generates a motor position source as

$$x_m = \frac{\lambda^2}{s^2 + 2\zeta\lambda s + \lambda^2} x_d \tag{9}$$

Producing a large impedance becomes a challenge. With a locked motor ($x_d = 0$) the external impedance is determined by the compliance

$$\frac{F_e}{V} = ms + b + k/s \tag{10}$$

We can slightly increase the apparent stiffness by driving the motor against the environment motion ($x_d = -\alpha x$). Unfortunately, this violates passivity and can quickly lead to stability problems, so that we consider the highest passively achievable impedance

$$Z_{LF,max} = \frac{k}{s} \tag{11}$$

To produce the lowest impedance, the motor must track the output position ($x_d = x$). But the lag in tracking causes some extension or compression of the series compliance

$$x - x_m = x - \frac{\lambda^2}{s + 2\zeta\lambda s + \lambda^2} x = \frac{s^2 + 2\zeta\lambda s}{s^2 + 2\zeta\lambda s + \lambda^2} x \tag{12}$$

and produces the external impedance

$$\frac{F_e}{V} = ms + \frac{bs + k}{s} \frac{s^2 + 2\zeta\lambda s}{s^2 + 2\zeta\lambda s + \lambda^2} \tag{13}$$

The minimum low frequency impedance is a damper

$$Z_{LF,min} = \frac{2k\zeta}{\lambda} \tag{14}$$

We note in particular both the maximum and minimum impedance depends on the series stiffness k. As such, the dynamic range in the SEA low frequency impedance is independent of k

$$\frac{Z_{LF,max}}{Z_{LF,min}} = \frac{\lambda}{2\zeta s} \tag{15}$$

In Figure 3 we show the resulting impedance for a low and a high stiffness value.

We can see the potential of variable impedance actuation. As k varies, we can achieve the super-set of impedances associated with each possible k value, greatly increasing the impedance dynamic range

$$\frac{Z_{LF,max}}{Z_{LF,min}} = \frac{k_{max}}{k_{min}} \frac{\lambda}{2\zeta s} \tag{16}$$

C. Force Dynamic Range

To examine the actuator's force dynamic range during task execution, we consider the largest force produced against a rigid contact and the smallest force developed while being externally moved or backdriven.

Like the impedance dynamic range, this is a result of a dynamic interaction. The force dynamic range is therefore a function of frequency. Specifically, the maximum force is limited by the maximum sustainable motor force $F_{motor,max}$ as well as the speed with which the motor can stretch any elasticities in the transmission. Assuming a sinusoidal force profile and a maximum motor speed $v_{motor,max}$, the largest achievable force is

$$F_{max} = \min(F_{motor,max} \quad , \quad \frac{k}{s} v_{motor,max}) \tag{17}$$

We note that the minimum force produced by the actuator when externally driven depends on the specific motion. For low frequency motions this is proportional to the low frequency impedance

$$F_{min} \propto Z_{LF,min} \tag{18}$$

For actuators with fixed elasticity, assuming the motor is speed-limited, we consider the force produced by the damper of (14) and the maximum force of (17) to find a dynamic range independent of stiffness

$$\frac{F_{max}}{F_{min}} \propto \frac{\lambda}{2\zeta s} v_{max} \tag{19}$$

As before, this suggests that variable impedance actuation can greatly increase the force dynamic range.

$$\frac{F_{max}}{F_{min}} \propto \frac{k_{max}}{k_{min}} \frac{\lambda}{2\zeta s} v_{max} \tag{20}$$

V. Experimental Verification

To verify the benefits of variable impedance actuation to achievable impedance and force ranges, we performed experiments using an actuator test bed that allowed several different elasticities to be introduced in series with a highly-geared DC motor. Tests were performed using a low stiffness, high stiffness, and inelastic coupling. The inelastic coupling exhibited a structural compliance of $K = 146$ Nm/rad in Experiments 1 and 3. The additional elements required in Experiment 2 further lowered the structural compliance to $K = 43$ Nm/rad. Furthermore, the damping ratio of the resonances for k_{low}, k_{high}, and K were found to be .33, .7, and 1, respectively. The parameters of the experimental setup are:

$$\begin{aligned} k_{low} &= 2.2\ Nm/rad & k_{high} &= 37\ Nm/rad \\ k_p &= 1050\ Nm/rad & k_f &= 9.77 \\ kd &= 7.5\ Nms/rad & B &= .264\ Nms/rad \\ m &= .000074\ kgm^2 & M &= .0359\ kgm^2 \end{aligned}$$

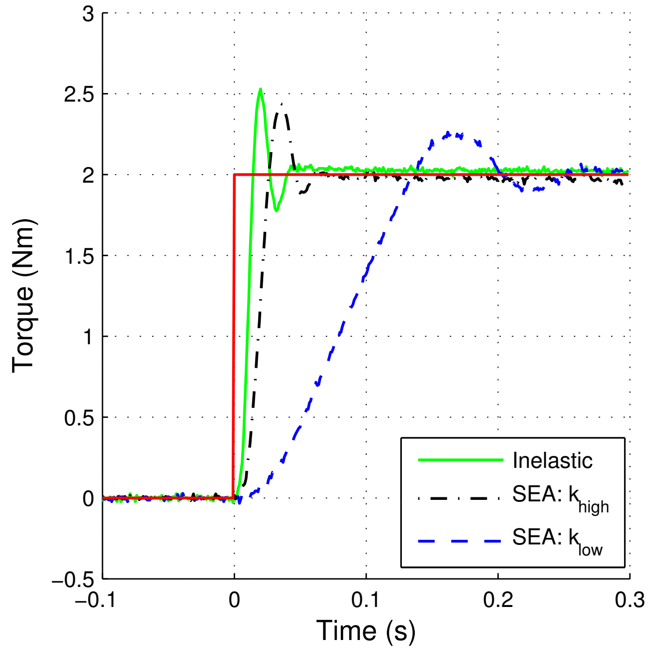


Fig. 4. Step Responses in Torque for the Inelastic Actuator and SEAs

A. Experiment 1: Actuator Torque Steps

We first performed a sequence of torque steps to verify the basic system behavior. In Figure 4 we see the response in all three actuator configurations. Note in particular that a softer SEA requires a much larger motor motion and hence takes substantially longer to reach the desired torque level. With reference to Table I, we recall that SEAs trade off available force bandwidth for the safety and low mass benefits of series compliance.

B. Experiment 2: Impedance Ranges

Next, we confirmed the impedance dynamic ranges derived above theoretically. In all three configurations, the actuator was excited by an additional external force source driving F_e. We performed the system identification with the actuators locked as rigidly as possible and with the actuator producing as little force as possible. Using the resulting force and velocity data, we plot the experimental minimum and maximum actuator impedances for the inelastic and series elastic actuators in Figure 5 and Figure 6, respectively.

Comparing Figure 5 to Figure 2 and Figure 6 to Figure 3, we see good agreement between our predicted impedance ranges and the observed impedance data. The minimum impedance represents a damper while the maximum follows a stiffness. Allowing the series elastic element to vary improves the impedance dynamic range.

C. Experiment 3: Force Ranges

To confirm the force dynamic ranges, we performed two tests. First we produced the largest force possible using the actuator over a range of frequencies, as shown in Figure 7. This was accomplished by commanding the maximum motor

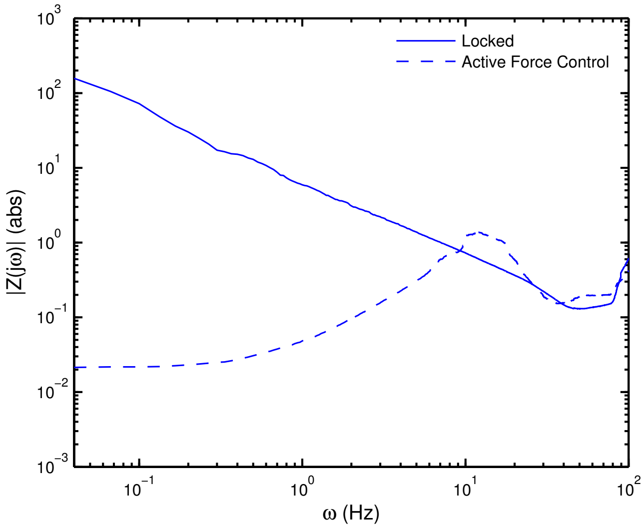


Fig. 5. Experimental Impedance Range for the Inelastic Actuator

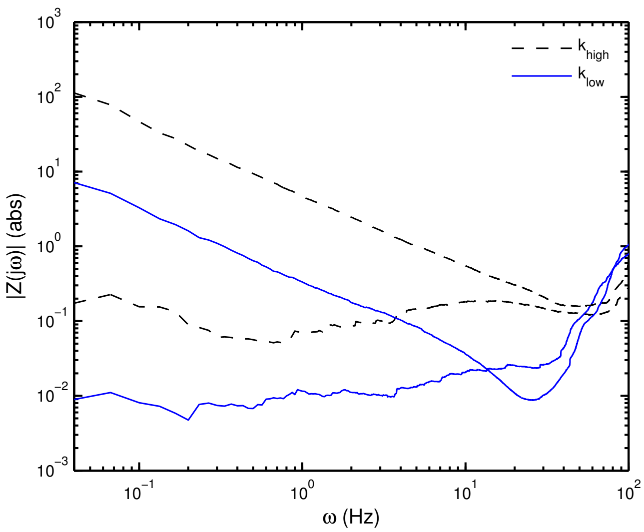


Fig. 6. Experimental Impedance Range for the Two SEAs with Low and High Stiffness

torque against a rigid load. The softer compliance requires the motor to travel a greater distance in a finite time and hence builds up less torque. At very low frequencies we experienced stiction limiting the maximum torque.

In the second test we backdrove the actuator manually over a range of frequencies while controlling the actuators to zero force. In Figure 8, we see that with more compliant actuators, the required interaction forces are smaller.

This suggests that force dynamic range is increased in a variable impedance actuator, as the actuator will be able to quickly produce large forces when stiff, and reliably present small forces when compliant.

VI. Conclusions

Many robots use highly geared motors with inelastic transmissions to produce large forces and provide high

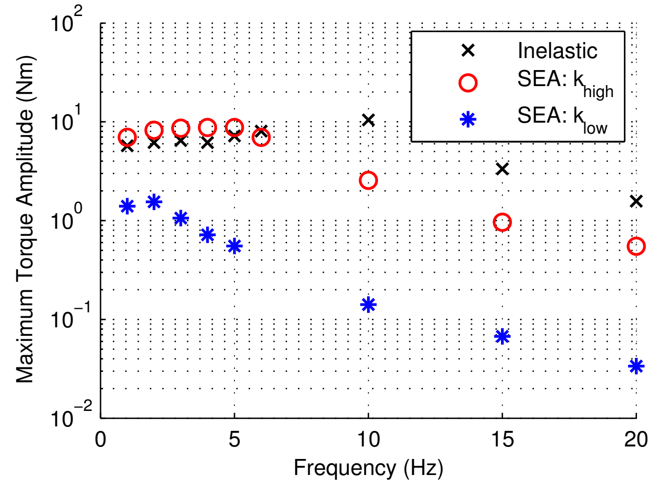


Fig. 7. Maximum Forces Achievable by the Actuator Configurations for a Range of Frequencies

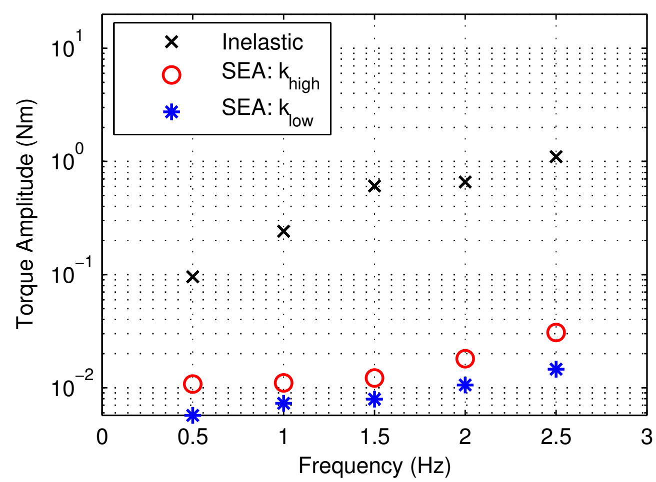


Fig. 8. Forces Experienced during Backdriving of the Actuators Controlled to Produce Zero Force

force bandwidth, supporting good disturbance rejection. Conversely robots with series elastic actuation offer great benefits to energetic tasks, such as locomotion or throwing. They also improve safety, reducing the force and energy of impacts.

Yet all these fixed impedance actuators show a limited dynamic range. Inelastic or stiff actuators can expose the environment to large friction forces and prevent delicate tasks. Soft actuators struggle to provide large forces for heavy loads.

Only a physically variable impedance, such as a physically variable elasticity, promises to retain the advantages of both. It scales impedance and force dynamic ranges with the magnitude of physical variation. In this work we have illustrated this benefit and summarized previously known benefits including higher safety and performance, better range of task capability, the ability to overcome controller limitations, tunable gait dynamics, and more efficient energetic task completion.

With the advantages of variable impedance actuators, it is our hope that work will continue on developing simple and reliable designs that will allow their implementation in a wider range of robotic applications.

ACKNOWLEDGMENT

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