# Improvements to Series Elastic Actuators

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***Abstract*—Actuators must be safe when interacting with humans, even in unexpected situations. Safety requires low impedance (low forces for a given perturbation) at all frequencies, not only in the actuator's stable bandwidth. Series Elastic Actuators (SEAs) are capable of achieving low impedance across all frequencies, though their force-frequency saturation envelope is decreased as a result. This paper examines ways to increase the force fidelity of SEAs by introducing inner control feedback loops and using appropriate sensor location. Findings include the superiority of a low fidelity sensor distal to stiction sources over a high fidelity sensor proximal to stiction and the superiority of an inner position feedback loop over an inner velocity feedback loop.**

***Index Terms*— force control, low impedance, series elastic actuator.**

## I. Introduction

High fidelity versions of conceptually classical robots have often been used for interaction with people because they are capable of achieving high torques and speeds. Many term these robots as having low-impedance if their actuator's impedance is low in the controllable bandwidth. At uncontrollable high frequencies that result from unplanned collisions, however, conventional robots – even ones with high force fidelity – have high impedance and become hazardous to people. The problem is exasperated by the low torque densities common in electromagnetic motors, which require high gear ratios to obtain acceptable torque densities. These high gear ratios significantly amplify the inertia of the actuator, creating high impedance systems. Perhaps the most common remedy in conventional robotics is to soften the blow of the robot with a compliant cover. As Zinn et al. have illustrated [1], however, more than five inches of cushioning would be needed to generate sufficient compliance to make a robot such as the Puma 560 safe when interacting with people. This bulkiness is unacceptable for many human-robot applications. Several new approaches have attempted to minimize the impedance of robots, including inertia reduction, passive impedance modulation, joint torque control, and increased compliance. After reviewing these techniques for use in anthropomorphic systems, improvements to increased compliance design will be suggested.

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## II. Technologies

Several methods are being investigated to achieve safer robot interaction with humans, including electromagnetic motor alternatives, inertia reduction, passive impedance modulation, joint torque control, and increased actuator compliance. These methods are examined below. All of these methods attempt to minimize one or more of the components of impedance. Impedance (Z) is generally considered to have stiffness (k), viscous (b), and inertial (m) components, although many methods focus solely on the stiffness or inertia of the system.

### *A. Electromagnetic Motor Alternatives:*

Popular torque generating alternatives to electromagnetic motors include pneumatic or hydraulic motors, McKibbon muscles, shape memory alloys, and electroactive polymers [2, 3]. All of these have been investigated in anthropomorphic systems to some degree, but have largely failed because of practical issues such as power consumption, low efficiency and slow response time. Pneumatic actuators are especially appealing because they are intrinsically compliant (and thus have low impedance at high frequencies). Both pneumatic actuators and hydraulic actuators, however, require compressed sources of air or fluid that are practically difficult to obtain and recharge. Pneumatic actuators have been used in prostheses in the past, but are currently not used because of these self-containment and accessibility difficulties.

### *B. Inertia reduction*

One way to reduce th e impedance of an actuator is to reduce the inertia of the actuator, a technique used by the PHANToM arm [4], WAM hand [5], and the base stage of the $DM^2$ [1]. This may be done by placing the actuators at the base of the robot and using a cable system to transfer power to the endpoint. This placement of the motors successfully reduces the inertia of the endpoint. The physical characteristics of cabling make large gear ratios difficult to obtain [6], reducing torque density and thus power efficiency.

### *C. Passive impedance modulation*

Several groups have created actuators that decouple the stiffness of an actuator from its force or position through nonlinear springs [7], spring length reduction [8], or other approaches [9-11]. These approaches successfully limit the impedance of the actuator. They all , however, require a second motor to decouple the stiffness from the motion of the actuator. This additional motor increases the size, weight, and power consumption of the robot.

### D. Joint Torque Control

Joint Torque Control (JTC) attempts to create high fidelity torque control by using high performance motors with minimal friction coupled with advanced controllers to achieve high torque performance at each joint in their controllable bandwidth. A recent example is the German DRL II [12]. The impedance of JTC controlled actuators above the controllable bandwidth, however, remains high, and it is precisely at this region where the effects of inertia dominate. As a result, JTC controlled actuators are still unsafe for unexpected collisions with humans.

Direct drive motors [13], a subset of JTC, exclude the gear transmission completely in an effort to minimize the motor inertia and achieve high fidelity torque control. They offer excellent force control as a result of minimizing friction and backlash. These motors require large diameters to generate appropriate torque interaction with humans, however, and have low power densities at slow speeds, making them unsuitable for use in portable anthropomorphic systems.

### E. Increased Compliance

The intentional increase of compliance in electromagnetic motors has been investigated in the past [14], and has recently gained support through the work of Pratt et al. [15], who have termed the concept a *series elastic actuator*. The concept has recently been explored by other groups [1, 16], and is illustrated in Fig 1.

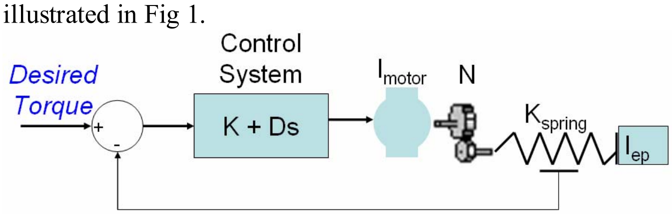


Fig 1. Series Elastic Actuator. Control system consists of proportional gain K and derivative gain D. The dominant feature of the motor is inertia, given the high gear ratio N. Spring has stiffness K, and interacts with the end-point of the actuator, with inertia $I_{ep}$.

Increasing compliance is desirable for two distinct reasons: 1) it increases force fidelity in the controllable frequency bandwidth, allowing for near-zero impedance, and 2) limits the impedance of the actuator to the stiffness of the spring at frequencies above the controllable bandwidth. This permits the use of non-backdrivable transmissions to conserve power. The introduction of compliance does not come without cost, however. The inclusion of compliance impairs the performance of the actuator by decreasing the frequency saturation envelope for given torques. Each of these reasons is further explained below.

#### 1) High Fidelity force control:

High proportional gains decrease the effects of nonlinearities such as stiction, improving force fidelity. If proportional gains are set too high, however, the system becomes unstable. A simple definition by Whitney [17] will be sufficient to illustrate the stability region:

$$0 < TGK < 1 \tag{1}$$

where T is the sampling period, G is the controller gain, and K is the combined stiffness of the actuator and environment. For a given sampling time, in order to increase the proportional controller gain it is necessary to decrease the actuator or environmental stiffness. It should be noted that the overall stiffness of the robot, from a control perspective, is not changed: it is merely shifted from the physical system to the controller [18]. This increase in controller gain minimizes the effect of plant nonlinearities such as friction, creating better force fidelity.

This increased force fidelity comes at a cost, however. All actuators have a torque-speed saturation envelope, an example of which is shown in Fig 2a. This envelope, when examined in light of the stiffness of the actuator, may also be thought of as a force-frequency force envelope (Torque frequency = spring stiffness * speed), as shown in Fig 2b. It may be seen that by reducing the stiffness of the actuator, one reduces the saturation frequency for a given force. Thus, through the introduction of compliance, one lowers the saturation envelope of the actuator. Provided one is beneath the envelop, increased compliance does not introduce any deleterious effects: it is only when saturation is reached that performance is reduced.

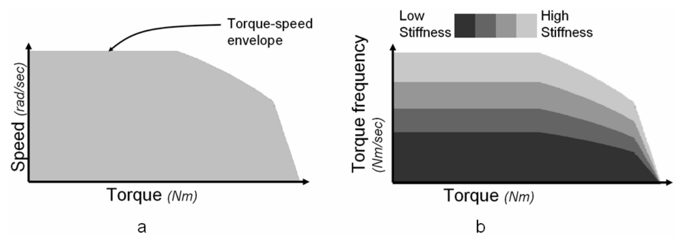


Fig 2: All motors have a speed-torque saturation nonlinearity (a), which limits the speed of the motor, dependent on the applied torque. The speed of the motor, combined with the stiffness of the actuator, illustrates the torque frequency of the actuator (Torque frequency = spring stiffness * speed). As seen in b) decreasing the stiffness decreases the torque-frequency saturation envelope for a given applied torque. As long as the motor is used inside the envelope, no decrease in torque frequency is observed for decreased stiffness.

#### 2) Impedance Saturation above controllable bandwidth

The impedance of the actuator given in Fig 1 is:

$$\frac{F(s)}{X(s)} = \frac{K_{spring} s^2 N^2 \mathrm{I}_{motor}}{s^2 N^2 \mathrm{I}_{motor} + K_{spring} + N(K + Ds)} \tag{2}$$

At high frequencies, the $s^2$ terms dominate and the impedance reduces to:

$$\frac{F(s)}{X(s)} \approx \frac{K_{spring} s^2 N^2 \mathrm{I}_{motor}}{s^2 N^2 \mathrm{I}_{motor}} \approx K_{spring} \quad as \quad s \to \infty \tag{3}$$

As a result, by intentionally decreasing the stiffness of the actuator to a level that is safe for human collisions, one ensures that the actuator will never create an unacceptable impact, even above the controllable frequency bandwidth.

## III. MODELING

#### 1) Modeling Sensor Placement

While it is always advantageous to minimize friction in an actuator, different actuator technologies respond better or worse in the presence of friction. Series elastic actuators (SEAs) offer substantial improvements for actuators that have high levels of friction [19], yet previous series elastic actuators have used virtually frictionless reciprocating ball screw transmissions or low gear ratios to avoid high levels of friction. While this has improved their performance, it has potentially masked optimal sensor placement.

SEAs have been conventionally instrumented with a displacement sensor in parallel with the compliant element, taking advantage of the increased motion of the compliant member to produce a high fidelity signal. This has been accomplished in linear series elastic actuators by placing a linear potentiometer in parallel with the spring, as illustrated in Fig. 3a. Linear potentiometers offer cleaner signals than load cells, which require high levels of amplification. This is not intuitive: potentiometers are often thought of as poor sensors. However, in the presence of large position changes due to the compliant member they are coupled with, they offer precise and clean control.

Robinson et. al [19] have demonstrated that any stiction on the motor side of the sensor is mitigated by the inclusion of a compliant torsional spring. However, any friction source between the sensor and the environment is not affected by the stiffness of the spring or the value of the feedback gain. As a result, a tradeoff exists between DC and AC error. A potentiometer will offer high fidelity control, but will not account for stiction (DC error). A load cell will offer low fidelity control, but will account for stiction. Thus for high levels of stiction, using a low fidelity load cell should increase performance. As a result, series elastic actuators should not automatically be fit with a position sensor in parallel with the compliant element; anticipated stiction in the design should play a crucial role in determining the optimal sensor location.

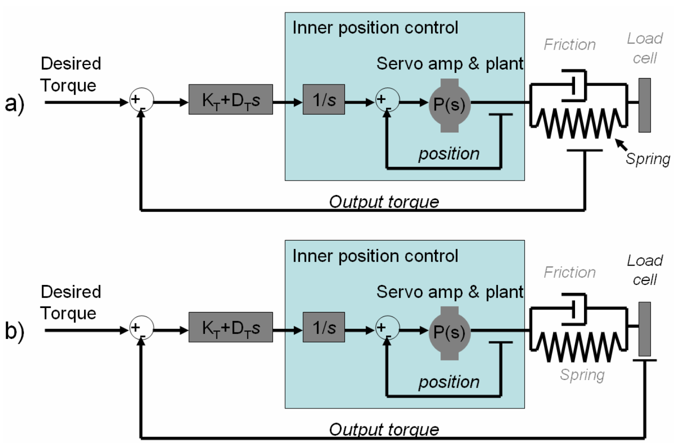


Fig. 3. Sensor placement:
a) Traditional parallel placement of a potentiometer offers a high fidelity signal, but cannot differentiate between parallel or distal friction sources and accurate force.
b) Serial placement of a load cell provides a poor signal due to high levels of required amplification, but may provides superior force control if it is placed distal to friction sources within the actuator.

### 2) *Modeling Feedback control*

Pratt et al. [20] have historically used an inner torque control loop since they are ultimately controlling torque. Due to the fact that series elastic actuators convert the accurate position output of a high impedance motor into a reliable force through the compliance of the spring, an inner velocity loop would appear to be a better choice. An inner velocity loop will attempt to attenuate the inertia of the rotor, effectively providing a flow source. As a result, as long as the motor is not saturated, an internal velocity loop should provide a higher fidelity position output with decreased system dynamics. Pratt et al. [21] recently demonstrated that this is the case. An inner velocity control loop is illustrated in Fig. 4a.

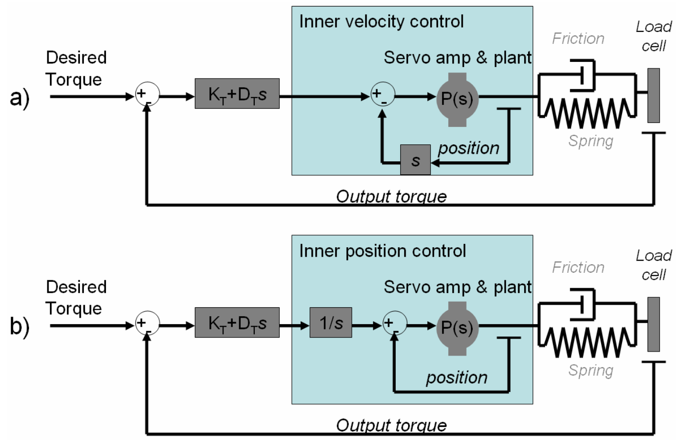


Fig. 4. a) Internal velocity feedback: The inclusion of an inner velocity control loop improves overall force control. The velocity signal is an integration of the measured position, obtained by Hall Effect sensors.
b) Internal position feedback: The inclusion of an inner position control loop should improve performance, since internal position control integrates the force error signal, rather than differentiating the position signal of the motor Hall effect sensors. Differentiating a signal amplifies high frequency (noise) components. The system dynamics are made more stable, but with an increased phase lag, as a result.

As illustrated in Fig. 4a, force error, which is proportional to velocity, is fed to the inner velocity control loop. Internal velocity control takes the position reading of linear Hall-effect sensors in the motor and differentiates it to achieve a velocity signal. Noise, which tends to dominate high frequencies, is amplified by differentiating the position signal. Differentiation of the position signal is not required, however: one may also integrate the force error signal and use an internal position control loop, as illustrated in Fig. 4b

Both of these methods will attempt to attenuate the inertia of the rotor by commanding a desired velocity, regardless of rotor inertia. An inner position loop should do so without adding increased noise. As a result, it should provide better force fidelity. There is a difference in the dynamic response as well, as illustrated by the transfer function for internal velocity control (Eq. 4) and internal position control (Eq. 5). As further shown by an illustrative zero-pole diagram and bode plot, using position control should increase both stability and phase lag, especially at higher frequencies.

$$TF_v = \frac{P(s)}{sP(s)+1} \tag{4}$$

$$TF_p = \frac{P(s)}{sP(s)+s} \tag{5}$$

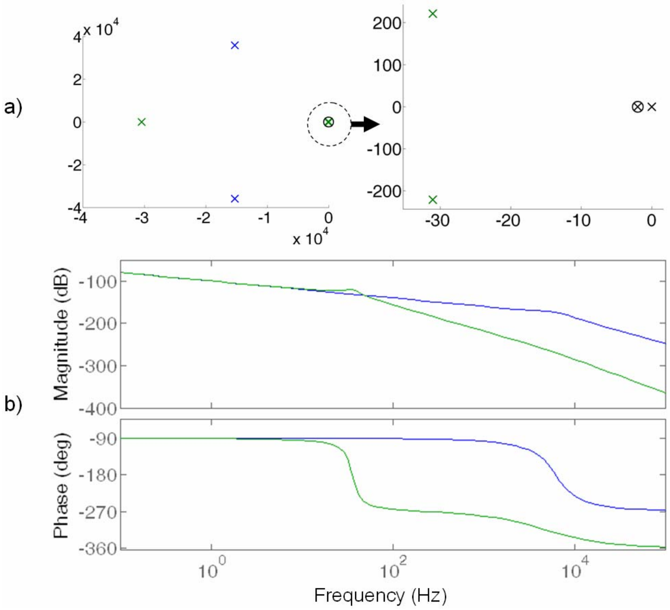


Fig. 5. a) Pole-Zero diagram of inner velocity feedback (blue) and inner position feedback (green). Poles or zero in common are plotted in black.
b) Frequency response of inner velocity feedback (blue) and inner position feedback (green).
Inner velocity control is less stable, but has decreased phase lag.

As a result, using an internal position loop should provide better performance than an internal velocity loop. We have conducted experiments to examine these hypotheses, as detailed below.

## IV. SEA Improvements

A linear actuator was constructed using a MicroMo[1] 1628T012 brushless motor with a 16:1 planetary gear transmission and a McMaster-Carr2 Acme 0.25″/rev lead screw, as illustrated in Fig. 6. The actuator was non-backdrivable below 5.8 N. Both a 2-quadrant MicroMo BLD-3502 servo amp and a 4-quadrant MicroMo MCBL 2805 motion controller were used to control the motor at 24V. Due to the lead screw and lack of bearings, this simple and inexpensive actuator has substantial amounts of friction that made force control impossible: proportional gains high enough to overcome friction proved to be too high to ensure stability, and frictional modeling [22] was of little help. This friction due to lack of bearings in the output shaft. A compliant 2100 N/m compression spring was placed in series with the actuator to allow for a higher proportional gain. This introduction of compliance created a stable actuator, and in the process provided what may be thought of as a worst-case series elastic actuator. Both a Load Cell Central[3] VLPB-10lb load cell and an ETI[4] LCP8S-10-10 kΩ linear potentiometer ($F \propto \Delta x$) were used to sense output force.

All controller gains were tuned using Ziegler and Nichols's [23] stability criterion for controller gains, as reviewed by Franklin et al. [24]. A 1N step response input against a stiff environment was used to tune the feedback terms. This method was chosen to obtain simple yet objective comparisons.

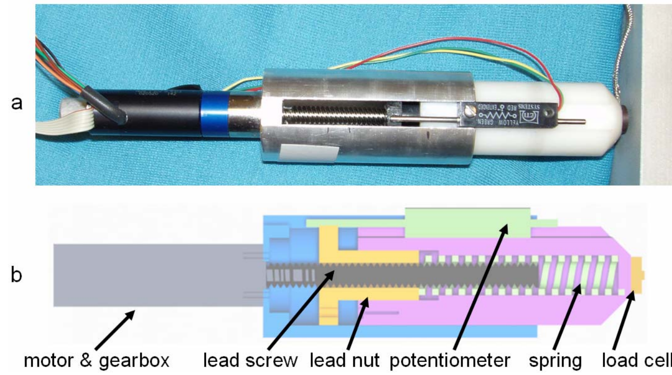


Fig. 6. Linear SEA with high levels of friction. High levels of friction in shaft made force control difficult, providing an ideal environment to examine the strengths and weaknesses of series elastic actuators.
a) Picture of actual actuator
b) CAD rendering of actuator

### A. Sensor placement

To examine sensor placement, the SEA was fit with a 10 kΩ linear potentiometer. When the system was tuned using the linear potentiometer, a proportional gain of 1.68 was achieved, significantly lower than the proportional gain of 9 achieved using the low fidelity load cell. The results are illustrated in Fig. 7. Notice the increased phase lag in Fig. 7a compared to Fig. 10b.

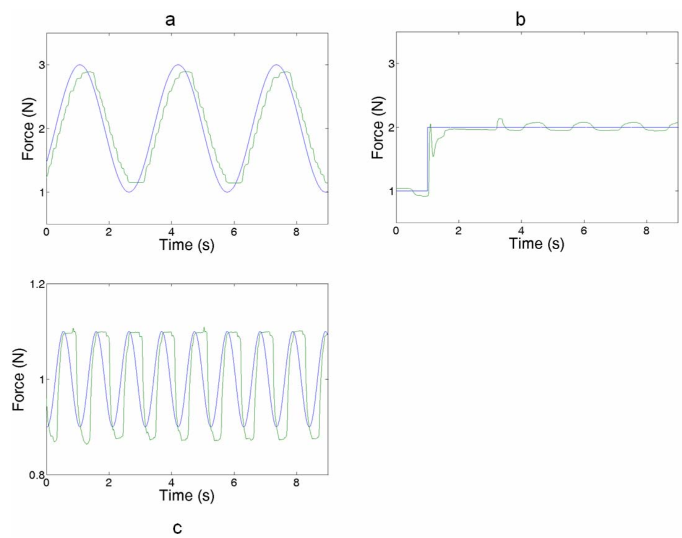


Fig. 7. Potentiometer sensor:
Controller gains: Proportional force gain (K) = 1.68, Derivative force gain (D) = 0.382, as determined using the Nichols and Zeigler stability tuning method.
a) Large force sinusoid response, b) Step response, c) Small force sinusoid response (note axis not zero)

### B. Inner control

Fig. 8 illustrates the results of force control for the linear SEA. The fact that stable force control is achievable at all is impressive given the high levels of friction, but the high levels of friction, combined with the introduction of compliance, create a system that is underdamped for increasing forces and overdamped for decreasing forces.

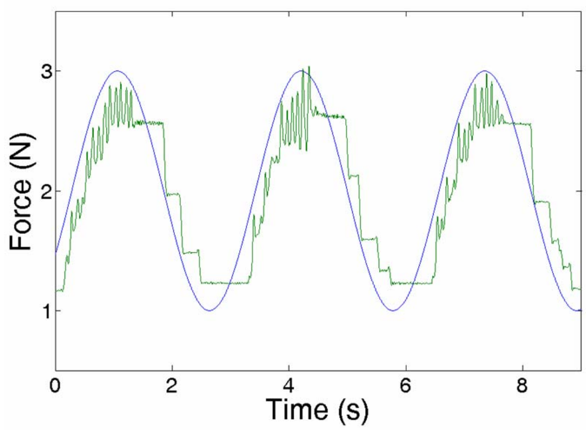


Fig. 8. Force control of a linear SEA with no internal control. No stable force control was achievable without the inclusion of a spring, illustrating the ability of increased compliance to compensate for high levels of friction. High levels of friction combined with compliance create an underdamped system for increasing forces and an overdamped system for decreasing forces.
Controller gains: Proportional force gain (K) = 0.258, Derivative force gain (D) = 0.006, as determined using the Nichols and Zeigler stability tuning method.

Adding an internal proportional-integral (PI) velocity feedback loop significantly increases performance, as illustrated by the improvement of Fig. 9b compared to Fig. 8.

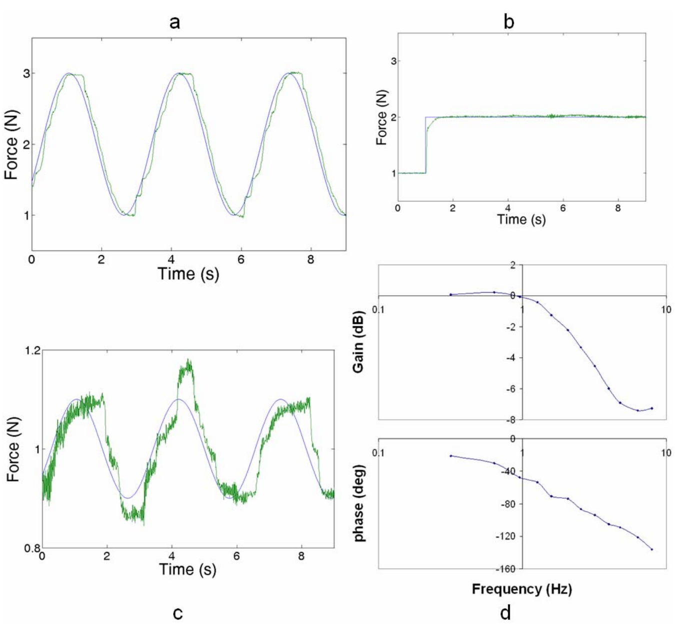


Fig. 9. Internal velocity feedback.
Controller gains: Proportional force gain (K) = 1.0, Derivative force gain (D) = 0.014, as determined using the Nichols and Zeigler stability tuning method.
a) Large force sinusoid response, b) Step response, c) Low force sinusoid response (note axis not zero), d) Bode plot

When an internal position loop is used, the force feedback proportional gain is increased 9 times and the frequency bandwidth is tripled compared to an inner velocity control loop. Results from using an internal position control loop are illustrated in Fig. 10. Thus, it seems advisable to use inner position control as opposed to inner velocity control.

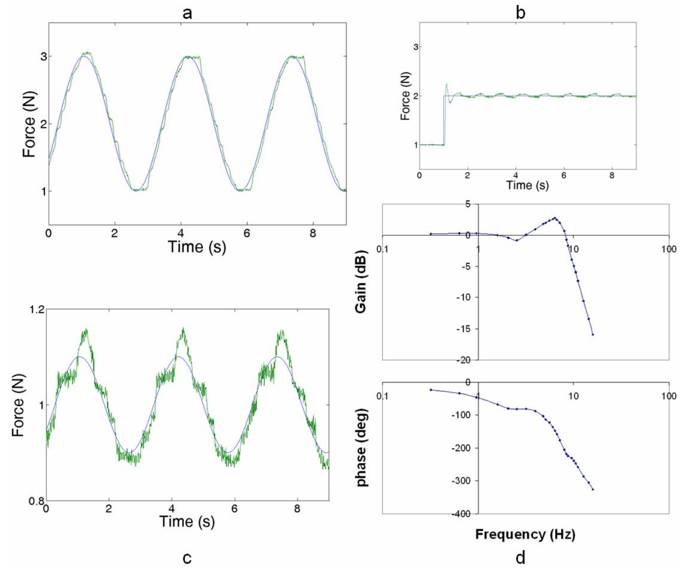


Fig. 10. Internal position feedback.
Controller gains: Proportional force gain (K) = 9.0, Derivative force gain (D) = 0.3125, as determined using the Nichols and Zeigler stability tuning method.
a) Large force sinusoid response, b) Step response, c) Low force sinusoid response (note axis not zero), d) Bode plot

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### C. *Summary of results*

Table 1 reports proportional gain and frequency bandwidth of the various control schemes. From these results, it seems apparent that introduction of compliance, internal position control, and a sensor in series with the actuator distal to any friction sources provide the highest fidelity force control.

**Table 1**
**Comparison of different control schemes**

Inner loop position control, coupled with a load cell and a compliant element, provides the highest proportional gain and frequency bandwidth.

| Stiffness | Inner loop | Sensor | Proportional gain | Frequency bandwidth |
|---|---|---|---|---|
| ~ ∞ | No inner loop | Load cell | No stable gain | N/A |
| | Position control | Load cell | .192 | N/A |
| 2100 N/m | No inner loop | Load cell | .258 | N/A |
| | Velocity control | Load cell | 1 | 3 Hz |
| | Position control | Load cell | **9** | **10 Hz** |
| | | Potentiometer | 1.68 | 1 Hz |

## V. Discussion

The addition of an inner position control loop as opposed to an inner velocity control loop seems logical. Velocity sensors such as tachometers are only accurate at high speeds. Although robotic actuators operate at high frequencies, they often operate at low velocities, even in the presence of reduction gear ratios. As a result, position information acquired through encoders or Hall Effect sensors is usually differentiated or filtered to obtain velocity data. It makes more sense to use the original, accurate position information obtained by the position sensors in the motor.

The placement of a displacement sensor in series with the actuator distal to any friction sources, as opposed to in parallel with the compliant element, also makes sense. At some point, there is a tradeoff between noise level and friction. The high levels of friction present in this actuator have tipped the balance in favor of noisy torque control. Low levels of friction might tip the balance in favor of indiscernible friction. It should also be acknowledged that for a linear series elastic actuator, a load cell is substantially more expensive than a linear potentiometer. The increase in performance must be balanced against the increase in cost.

In an effort to practically realize these findings in a prosthesis, we have constructed a prosthetic elbow. The torsionally compliant member does not increase the size of the elbow because the spring is wrapped through the middle of the frameless motor and harmonic drive, as illustrated in Fig. 11a. In addition, we have used a modified cross section for our torsional member based on dimensional modeling and finite element analysis, which indicates the new shape, termed a spandrel, offers increased geometrical resilience [25-27]. In other words, the spandrel shape can deform more without plastically deforming. This shape is illustrated in Fig. 11e. Future work will test whether or not people with amputations prefer the impedance control that this actuator can provide in an attempt to explore the previous findings of Abul-Haj [28].

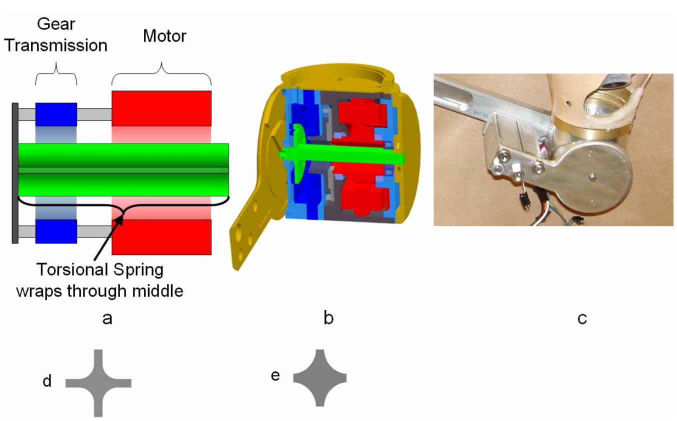


Fig. 11. Prosthetic Elbow.
a) Torsional spring is wrapped through the middle of the harmonic drive and frameless motor.
b) shows a CAD rendering of the actual design, and c) shows the actual device.
d) shows the conventional cross section of the torsional spring
e) shows a more resilient cross shape, that may deform more without plastically deforming.

## VI. Conclusion

Robots that interact with humans must have low impedance across all frequencies; not only those frequencies where they are controllable. Decreasing the stiffness of the plant allows for increased controller gains, creating a higher fidelity system without affecting the performance of the actuator below the saturation envelope. Increasing compliance does decrease the saturation envelope. Providing an inner position loop and using a sensor distal to all friction sources provides increased proportional gain, better force fidelity, and higher controllable bandwidths.

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