Direct impedance modulation of passive antagonistic pneumatic artificial muscles

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Introduction

Traditional control methods for pneumatic artificial muscles (PAMs), which focus primarily on trajectory [1] or force control [2], fall short in achieving effective impedance modulation for PAMs. This study explores techniques for direct impedance modulation in antagonistic PAMs. Using empirical force-deflection data from a single PAM, we developed an inverse model to achieve impedance modulation with joint antagonism, targeting specific impedance parameters and equilibrium point.

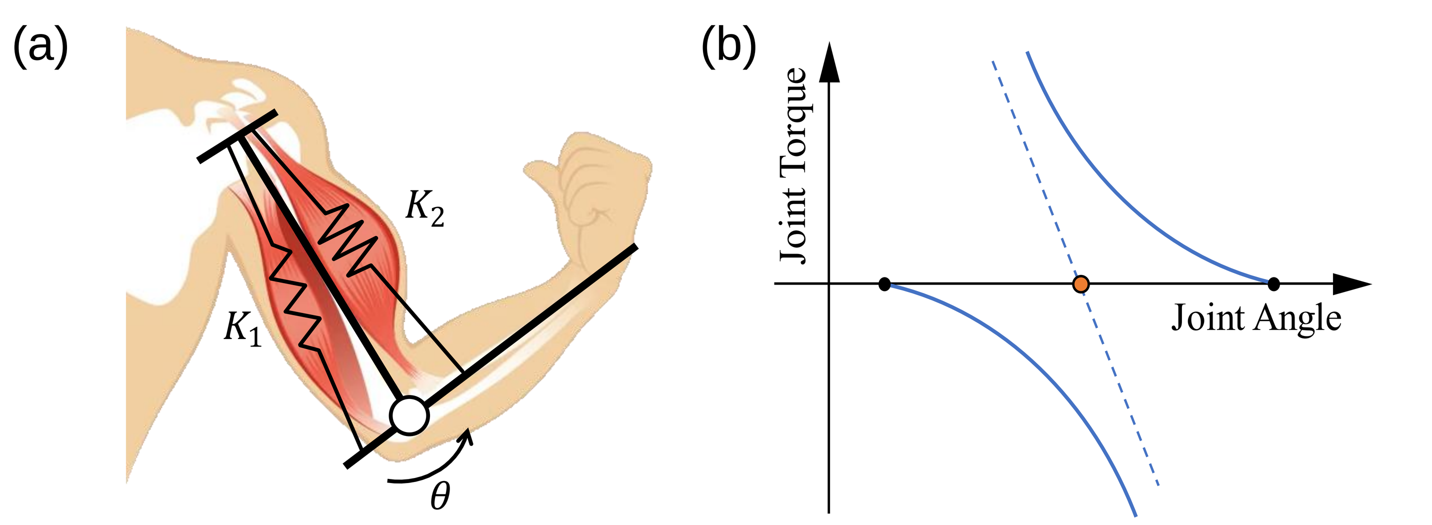

Figure 1. Human elbow can adapt to different daily tasks by adjusting the length and stiffness of the muscles. (a) Simplified diagram of human elbow anatomy. (b) Theoretical force-deflection curves.

Setups

Data and actuators are collected and controlled by a BeagleBone Board, the setups are as shown in Figure 2.

- The single PAM experimental platform consists of a PAM in series with a load cell and a linear actuator, a linear potentiometer is attached to the PAM for length measuring.
- The antagonistic experimental platform consists of two PAMs configured in opposition coupled via a shaft that is equipped with an encoder and connected to a DC motor.

The PAM pressure is controlled by a valve controller with a fixed pulse width signal following by a refractory period for checking PAM state.

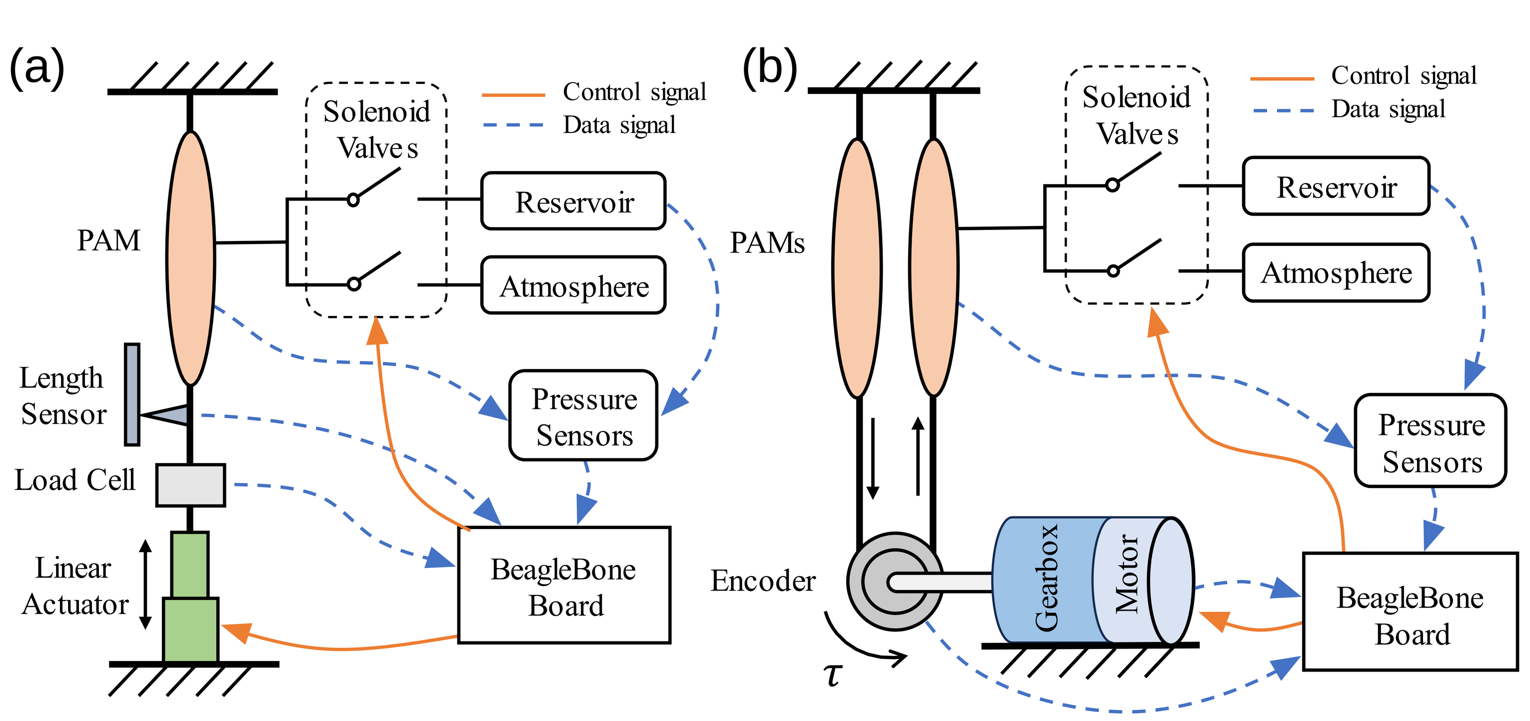

Figure 2. Experiment setups. (a) Single pneumatic muscle property test setup. (b) Antagonistic setup for system identification and verification.

Inverse Model

To develop an inverse generative model for use in an antagonistic PAM configuration, we need to empirically investigate the force-deflection characteristics of a single PAM. Single PAM property test data shows the PAM force at given initial pressure (P_0) and displacement (Figure 3), after mapping PAM force and length into torque (τ) and angular deflection (θ) using the geometric properties of the antagonistic setup, we can get:

$$\tau^{\sigma} = f_{\tau}^{\sigma}(P_0, \theta)$$

$$P^{\sigma} = f_{P}^{\sigma}(P_0, \theta)$$

where σ means two states of PAM, loading (lengthening) and unloading (shortening). Then we can generate a net torque curve as shown in figure 1 (b) as a function of deflection angle:

$$\tau_{net}^{\sigma} = f_{\tau}^{\sigma}(P_0, \theta) - f_{\tau}^{\neg\sigma}(P_0, -\theta)$$

The joint equilibrium point corresponds to the x-intercept, and the joint stiffness corresponds to the slope. Then we can obtain a forward generative model with $[P_1, P_2]$ as inputs, $[\theta_0, K]$ as outputs. By inverting this model, an inverse generative model for implementing passive impedance modulation is developed.

System Identification

For system identification, we modeled the system as a second-order system, designed a model function, f_m, to calculate $\ddot{\theta}$ from external joint perturbation and response:

$$\ddot{\theta} = f_m(P) = [\tau - B\dot{\theta} - K(\theta - \theta_0)]/I$$

where $\mathrm{P} = [I, B, K, \theta_0]$. Next, we formulated optimization function aimed at minimizing the difference between the actual joint angle and the fitted joint angle, to determine the system's impedance and equilibrium point terms:

$$\min_{P} \left\| \theta - \ddot{\hat{\theta}} \right\|_2$$

$$s.t.\ \ \ddot{\hat{\theta}} = f_m(P)$$

where $\ddot{\hat{\theta}}$ is the fitted angle from model function.

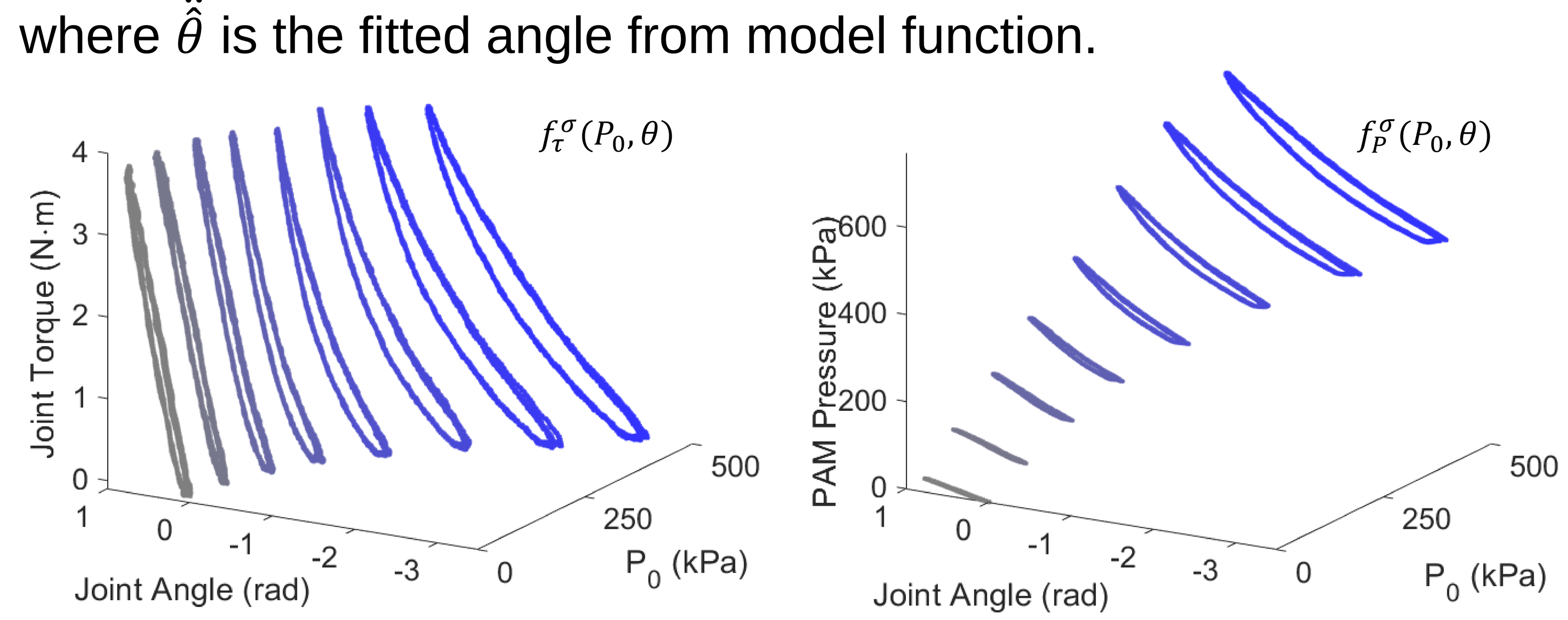

Figure 3. Torque and pressure functions include hysteresis behavior at different joint angle with different initial pressure.

Results

We can input several desired joint stiffness and equilibrium point combinations, and use the inverse model pressure outputs to inflate PAMs. For each input, we applied a perturbation 10 times in clockwise and counterclockwise directions, resulting in 20 trials per test. The calculated the equilibrium point and the joint stiffness for each trial are as shown in Figure 4.

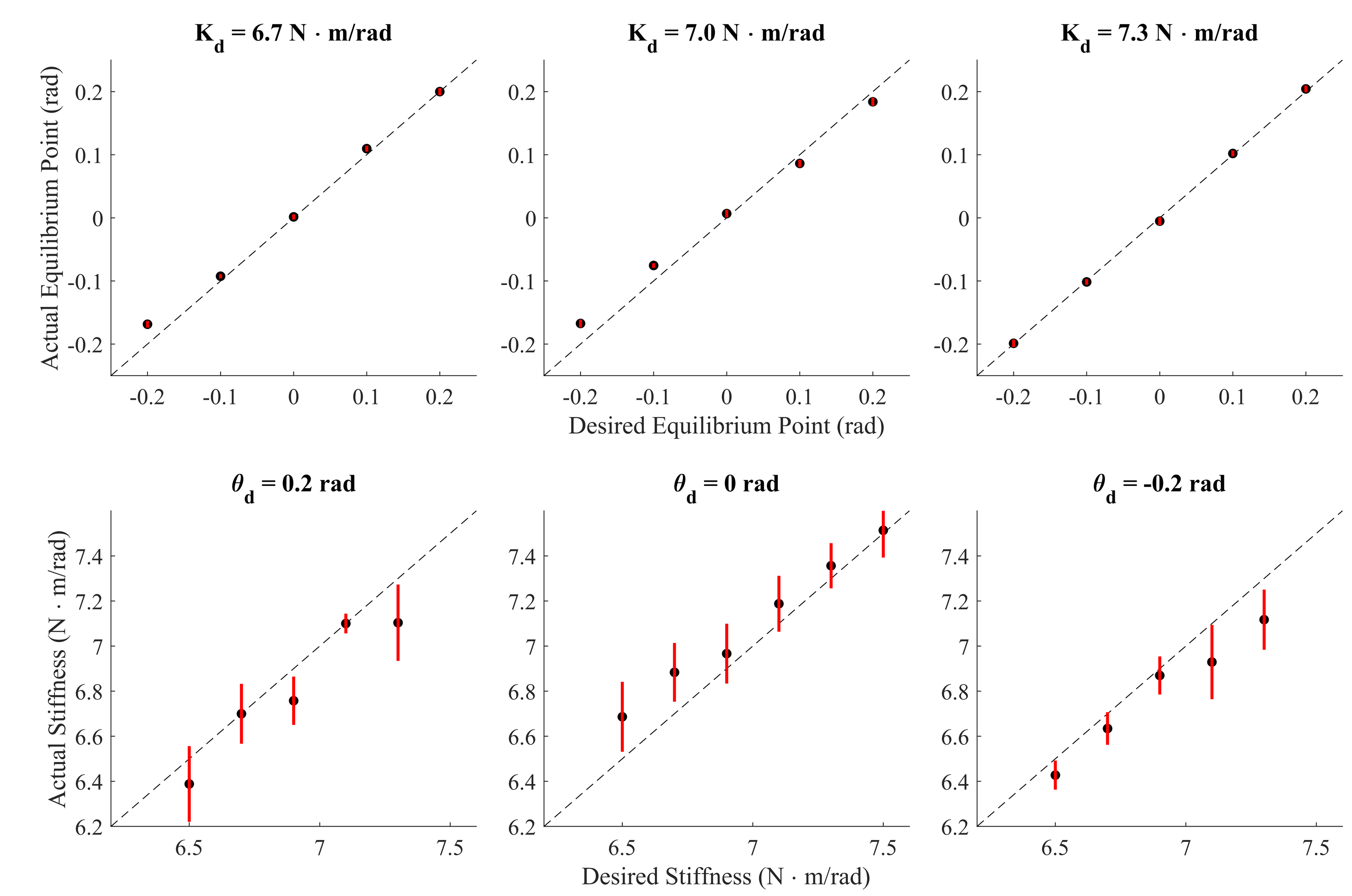

Figure 4. Comparison of desired joint angle/stiffness and actual joint angle/stiffness from inverse model. The black dot represents the mean value of 5 test trials, and the red bar indicates the standard deviation.

Conclusion

We characterized a commercial pneumatic muscle and proposed an inverse model for direct impedance control. The model accurately controls joint impedance and the equilibrium point with minimal error. This study offers an efficient method for model-based impedance modulation, especially reducing the effort required to build wearable robots for patient rehabilitation and support in daily activities.

References

[1] Q.-T. Dao, D.-H. Mai, D.-K. Nguyen, and N.-T. Ly, "Adaptive parameter integral sliding mode control of pneumatic artificial muscles in antagonistic configuration," Journal of Control, Automation and Electrical Systems, vol. 33, no. 4, pp. 1116–1124, 2022.

[2] F. Connolly, C. J. Walsh, and K. Bertoldi, "Automatic design of fiber-reinforced soft actuators for trajectory matching," Proceedings of the National Academy of Sciences, vol. 114, no. 1, pp. 51–56, 2017.

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