Design of a Simplistic Variable Stiffness Actuator

Sajiv Shah and Brad Saund

***Abstract*— Robotic joints that consist of mechanisms that allow for variable impedance have become highly desirable as they allow for an optimization in compliance, speed, and precision. Humans achieve variable stiffness at many joints using antagonistic muscle pairs, in which one muscle contracts while the other relaxes . Existing mechanisms, such as Series Elastic Actuators (SEAs), utilize an elastic component such as linear springs between the motor and output to measure loads on a joint. The use of elastic elements that do not have forces that are directly proportional to their stretch length - in other words do not follow hooke's law - in series elastic actuators would allow an actuator to have a variable amount of stiffness in relation to the initial extension length of the elastic. We propose a modified series elastic actuator that uses torsional springs in a linear fashion as the elastic component. When pulled outward on their ends, torsional springs have a non-linear relationship between their extension length and force, which allows a joint to achieve a variable amount of stiffness when the springs are extended by an additional motor.**

I. INTRODUCTION

As robots move from confined work-spaces to fluid collaborative spaces, they develop new requirements. Robots working in isolated and confined spaces are often rigid and extremely precise, which is beneficial as it does not require the robot to react to its environment. However, robots in collaborative space must be able to react to their dynamic surroundings, as collisions are common. Thus, compliant robot joints [1] were developed as a means to solve the safety problem.

Human muscles and tendons allow joints to have a variable amount of stiffness [2] based on the task they must perform. When jumping, for example, the leg joints must be stiff in order to launch off the ground. However, when landing, the muscles must relax and act compliant in order to ensure a soft landing.

In contrast to active compliance, which requires sensors, controllers, and constant real-time adjustment, passive compliance is achieved by an elastic component between the motor and the actuator output [3]. These elastic elements create a compliant joint, and as seen in the design of SEA[4], also allow for force sensing. In the case where a sensor is placed on the motor joint and the actuator output, the difference in the angular displacement represents how much the springs were stretched or shortened. If the spring follows hooke's law, which it should, then the relationship between the spring extension and force is:

$$k = \frac{F}{x} = constant$$

Variable Stiffness Actuators (VSAs) [5] provide a benefit over SEAs as they incorporate stiffness control in their mechanisms in addition to passive compliance. Antagonistically actuated joints[6], which are biologically inspired, use two elastic components with non-linear relationships between their extension and force. These elastics have non-constant spring stress/strain relationships, represented by:

$$k(x) = \frac{dF}{dx} \neq constant$$

Various works implement variable stiffness, some using non-linear elastics such as leaf springs [7], while others change the structure and configuration of elastics[8] . Compared to previous designs, our approach is simpler and lighter. In section II, we present our method for achieving variable stiffness by modifying a SEA with a non-linear elastic system and an additional motor to extend the elastics and add an antagonistic effect to the actuator. In section III we present our preliminary experiments and data.

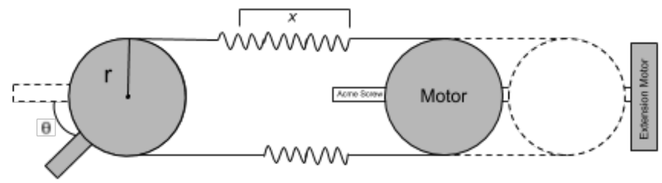


Figure 1. Drawing of a Series Elastic Actuator, with elastics between the motor and joint

II. METHOD

The relationship between the stiffness on a compliant joint which is applied on it by the springs as shown in figure 1 can be represented using the function k(x),and variables r and θ, where k(x) is the spring stress/strain as a function of extension, r is the radius of the actuator output pulley, and θ is the angular displacement of the pulley:

$$F_{spring1} = k(x + r\theta) \cdot (x + r\theta)$$
$$F_{spring2} = k(x - r\theta) \cdot (x - r\theta)$$
$$T_{net} = F_{spring1} \cdot r - F_{spring2} \cdot r$$
$$T_{net} = r \cdot [k(x + r\theta) \cdot (x + r\theta) - k(x - r\theta) \cdot (x - r\theta)]$$

If k(x) is constant in the equation above then the initial value x will not impact the stiffness. However, if k(x) is not constant, then the use of a non-linear elastic system and an additional actuator for changing the initial extension, x, will allow for calculated variable stiffness.

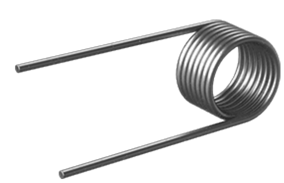


Figure 2. Torsion Spring from McMASTER-CARR

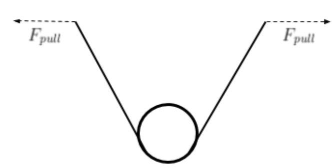
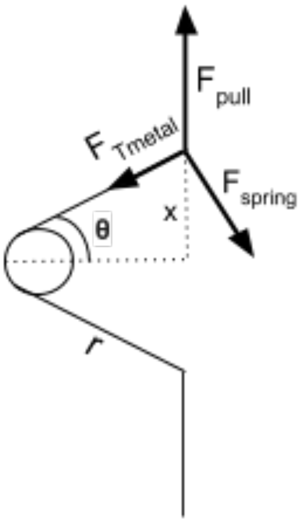


Figure 3. Linear pull on ends of torsional spring

Torsion springs (figure 2) are often used in mechanisms where a rotational object needs a force applied on it. However, as shown in figure 3, pulling on the ends of a torsional spring also produces a linear force inwards, just like a normal spring. The linear stress/strain relationship k(x) of a torsional spring in this configuration is written as:



$$k(x) = \frac{F_{pull}}{x}$$

$$k(x) = \frac{\kappa \cdot \theta}{r^2 \cdot \sin(\theta) \cdot \cos(\theta)}$$

$$k(x) = \frac{\kappa \cdot \arcsin(\frac{x}{r})}{x \cdot \sqrt{r^2 - x^2}}$$

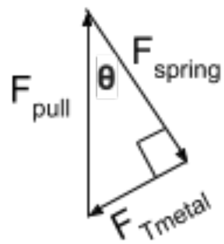


Figure 4. Force diagrams of torsional spring used linearly

When a torsional spring is used in a linear manner, the linear spring stress/strain function k(x) is not constant, meaning that changing the initial extension of the spring would yield different torques on the actuator output.

III. Preliminary Experiments

Experimentally, we needed to determine if the torsional springs matched the k(x) function that we mathematically predicted. Using a scale, we measured the force and stretch length of a torsion spring and plotted those values (figure 5).

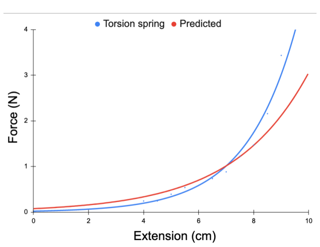


Figure 5. Linear spring force vs. linear extension

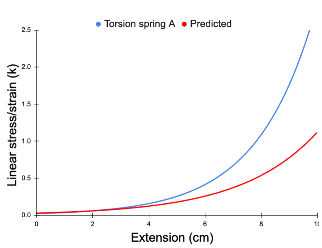


Figure 6. Linear stress/strain vs. linear extension

Looking directly at the graphs (figure 5 and figure 6), it is evident that the relationship between the force and extension is non-linear. In order to create a system that can implement torsional springs accurately, we created a system of torsional springs where they are added together to create a ladder like structure, which can be pulled at its two ends like a linear spring (figure 7). Using this system, we measured the local torsional stiffness of the actuator output at θ = 0 at different extensions to measure the stiffness, which we plotted into a graph (figure 8).

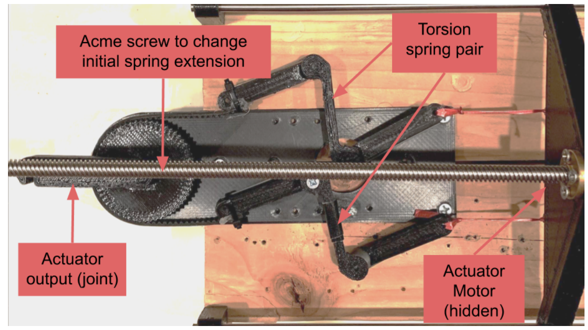


Figure 7. VSA with torsional spring as elastic component

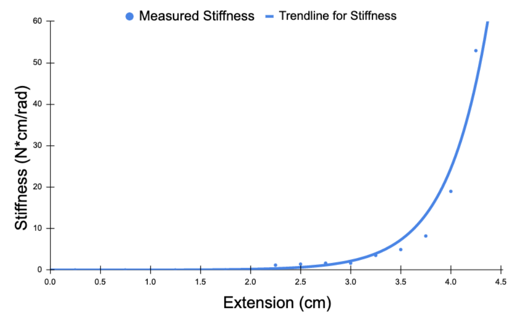


Figure 8. Stiffness of joint at different initial extensions

In a small range of extension, this actuator achieves a large range of usable variable stiffness. This actuator allows robots such as bipeds to carry out various tasks using a single system, while also being compliant. This system could be highly valuable as it achieves variable stiffness in a very simple, lightweight manner, and allows for a single extension motor to work on two different actuators that are paired in a differential drive, reducing the number of motors required for variable stiffness. In the future we hope to refine our actuator and create a multi-link system that can demonstrate the benefits of our VSA design in a robot.

References

1. B. Vanderborght, A. Albu-Schaeffer, A. Bicchi, et al. “Variable impedance actuators: a review” Robot. Auton. Syst., 61 (12) (2013), pp. 1601-1614
2. Kearney RE, Hunter IW. System identification of human joint dynamics. Crit Rev Biomed Eng. 1990;18(1):55-87. PMID: 2204515.
3. S. Wolf, G. Grioli, O. Eiberger, et al. ”Variable stiffness actuators: review on design and components,” IEEE-ASME Trans. Mech., 21 (5) (2016), pp. 2418-2430
4. Pratt, G. and M. Williamson. “Series elastic actuators.” Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots 1 (1995): 399-406 vol.1.
5. Grioli, G., Wolf, S., Garabini, M., Catalano, M., Burdet, E., Caldwell, D., et al. (2015). Variable stiffness actuators: the user's point of view. Int. J. Rob. Res. 34, 727–743. doi: 10.1177/0278364914566515
6. M. Laffranchi, N. G. Tsagarakis, F. Cannella and D. G. Caldwell, "Antagonistic and series elastic actuators: a comparative analysis on the energy consumption," 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, MO, 2009, pp. 5678-5684, doi: 10.1109/IROS.2009.5354349.
7. L. Fang, Y. Wang. “Stiffness analysis of a variable stiffness joint using a leaf spring,” Intell. Robot. Appl. (2017), pp. 225-237
8. K.W.Hollander,T.G.Sugar,andD.E.Herring,“Adjustable robotic tendon using a ‘jack spring’,” in Proceedings of the IEEE 9th International Conference on Rehabilitation Robotics (ICORR’05), pp.113-118, July 2005