A Bio-inspired Spring Reinforced Actuator for a Legged Robot

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***Abstract*— This paper presents a novel spring reinforced actuator inspired by muscular hydrostats and exoskeleton existing in varies nature species. By applying this constraint to a soft actuator system, the actuator can achieve a balance stiffness and compliant. Experimental result and a demonstration of the actuator on a quad-pedal are shown.**

I. INTRODUCTION

Muscular hydrostats have long been a source of inspiration in the field of soft robotics. These structures have no underlying endoskeleton, and consist entirely of muscles, which make them flexible and conformable, yet dexterous manipulators. Inspired by many spineless animals, like earthworm[1] and octopus [2], recent growth in soft robotics revealed a way to perform various kinds of motions and flexibility of motions. Researchers originally sought to mimic these unique properties by employing silicone-bodied soft robots driven by specialized fluidic channels [3]. Many studies were successful in imitating these muscular hydrostats, producing safe and compliant robots that could be used in a range of fields like surgery [4] and search and rescue. Soft robots excel in environments where flexibility and adaptability are essential, but their performance lacks where high force or a fast-dynamic response is needed, ultimately limiting their usage in a range of tasks.

An approach to augmenting soft robot performance is through the use of hybrid mechanisms. Hybrid actuators integrate rigid components with soft structures in order to modify their actuation characteristics. One study proposed a soft actuator design inspired by crustaceans, using a hard exoskeleton with soft actuators inside them [5]. Short rigid plates could be mounted at different points along the length of the body to alter the bending profile. The exoskeleton could linearize the force and bending behavior, and was easily configurable, although the addition of external rigid components may not be ideal for fragile environments and limits the bending to one direction. In a similar fashion, Arthrobots [6] took inspiration from the legs of insects and spiders. They used thin, lightweight rigid links actuated by inflatable balloon joints in combination with antagonistic tendons to allow passive retraction.

In this study we propose to incorporate a flexible backbone into the body of a soft robotic actuator. The backbone is in the form of a spring which has anisotropic rigidity that allows lateral bending while being radially incompressible. The spring provides a continuum structure that can match the natural bending profile of the soft actuator, while augmenting it with a *passive* antagonistic mechanism that improves stiffness and response time. The restoring force of helical springs have also been shown to reduce hysteresis and enhance actuator's dynamics performance.

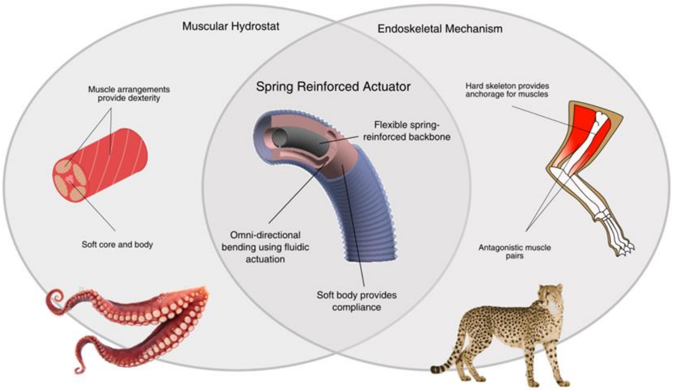

FIG. 1. Illustrating the concept of integrating muscular hydrostat and endoskeleton mechanism for spring reinforced actuator

The proposed hybrid actuator consists of a *closed*-coil spring integrated into the central lumen of a 3-chamber soft actuator. A *closed*-coil spring is used as opposed to the more common *open*-coil spring due to the pre-compression they have. We analytically characterize the transverse bending behavior of a *closed*-coil spring, and validate its effect after integration with the soft actuator. We then use it to constructs a quad-pedal robot for illustration.

II. METHODS

The overall design of the actuator are as follows:

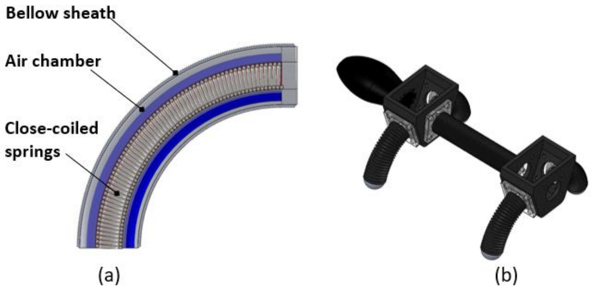

FIG. 2. (a) Section view of reinforced actuator during bending. (b) CAD drawing of the quad-pedal

To investigate the bending behavior of the spring reinforced actuators (SRA), analytical modeling of the closed-coil spring was first pursued. A bending test on close coiled springs is carried with following set up and a formula concerning the bending stiffness and the moment is deduced as follows:

The inclination changes per coil due to the moment M:

$$\theta_s = \frac{2\pi\left(GJ+EI\right)\left(-F_p r+M\right)r}{\left(3EI+GJ\right)GJ} \qquad (1)$$

where r is the spring radius, E is the young modulus, G is the shear modulus, I is the moment of inertia of spring coil, J is the polar moment of inertia of spring coil and R is the radius of spring coil.

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III. RESULTS

To evaluate the bending performance of the actuator, a tailor-made testing platform was built as shown. During testing, each actuator was clamped as a cantilever and mounted with groups of reflective tracking markers at the tip and mounted end. Four 200fps 3D tracking cameras (Vicon Vantage) tracked the actuator's 3D position and orientation based on the relative motion of two sets of tracking markers. The pressure sensor would then send its reading to the computer for monitoring.

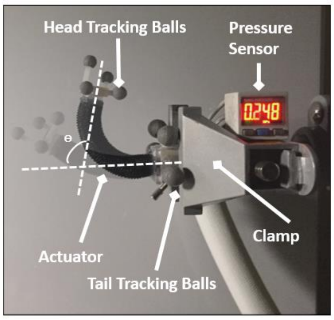

FIG. 3. Testing set-up and experimental results for actuator

The robot is allowed the tilt up and down repeatedly from 0 degree to 60 degrees. Motion is captured for bode plot. The bode plot in Fig. 5 highlights an improved result for the actuator with spring reinforcement. The soft actuator can not behave normal with more than 1.5Hz input. Meanwhile, the reinforced actuator can maintain a normal behavior with 5Hz input. The poor underdamping behavior of the soft actuator may be due to the soft material body, which are not able to exhaust air during deflation. With the present of the spring, there is a force to release exhaust air and repel to desired position.

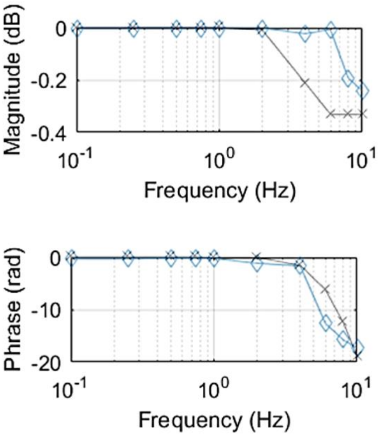

FIG. 5. Bode plot of the soft actuator (black) and reinforced actuator (blue)

IV. APPLICATION

To illustrate the balance between feasibility and stiffness, a quad pedal locomotion tasks is carried. The robot consists of 5 spring reinforced actuator, with 4 as legs and one as lumbar. The robot can walk on unstructured surface with compliance from soft actuator. Meanwhile, spring parts of the robot can provide an assisting structural support for manipulation and increased the dynamics behavior of the robot so that it could walk rapidly as a rate of 30mm/s on sand surface(Fig.5a) and 40mm/s on wood surfaces. (Fig.5b)

FIG. 5. (a) Quad pedal walking on sand surfaces; (b) on wood surface

V. CONCLUSION AND FUTURE WORK

Present soft fluidic actuators bring to the table compliant morphology, robustness and passive adaptability to unknown environments. However, this comes at the cost of force output and the manipulator's dynamic response. In this study, we proposed to integrate a closed-coil spring into a soft manipulator to improve those characteristics, while retaining the bending ability of the original manipulator and its material compliance. In our future work, we aim to further characterize the effect of the spring integration by also considering the soft robot material characteristics, and also investigate the impact of changing different spring parameters on overall performance. We will also aim to implement re-configurability of the robot, by allowing simple swapping of the spring based on the desired application.

ACKNOWLEDGEMENT

Our work is supported, in part, by the Croucher Foundation, the UK Engineering and Physical Sciences Research Council (EP/P010040/1, EP/N031768/1, EP/L016796/1, EP/L00058X/1), the European Union Horizon 2020 Research and Innovation Programme (671653), the Research Grants Council (RGC) of Hong Kong (17202317, 17227616 and 27209515), Signate Life Sciences Limited and Aptorum Group Limited.

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