Muscle-Tendon Complex-Inspired Deformable Exteriors as a Wire-Drive Extension

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1 Introduction

The animals are driven by the Muscle-Tendon Complex (MTC). Soft, internal-filling muscles protect the skeleton, nerves, and internal organs, and tendons are deformed in various ways to exert elasticity. Muscles are also known to have complex nonlinearities between force, velocity, and length [1]. In the case of robots, it is considered that the complex properties of the drive system may contribute to increase the variety of motion. There have been some studies that focus on this issue, such as the application of nonlinear spring units to a biped robot [2] and the application of nonlinear control to a robot arm using pneumatic artificial muscles [3]. However, the properties resulting from the shape and deformation of MTC have not been adequately studied. We investigated a wire-driven structure with an exterior that mimics muscles and tendons. For simplicity, we consider only two-dimensional planar deformations. Compared to the wire-only case, these exteriors protect the bone and joint components, the internal circuit boards, and the wires themselves (Figure 1(a)). In this study, we discuss the properties of this structure in terms of its behavior against wire winding.

2 Muscle-Tendon Complex-inspired deformable exteriors applicable to wire drive

An exterior that imitates bulging muscles is attached to the outside of the wire, which deforms following the contraction of the wire. This structure is combined with a rubber tendon to form a structure similar to a muscle-tendon complex (Figure 1).

2.1 Muscle Exteriors

In this study, the wire is wound by a muscle module [4]. The wire drive has so far only substituted the contraction function of the muscle. On the other hand, the structure used in this study has a muscle exterior attached to the wire so that it expands in the radial direction in response to contraction when driven. The polytetrafluoroethylene (PTFE) plates used as the material have self-lubricating properties that prevent the generation of unexpected forces due to environmental contact or muscle-to-muscle contact, which may be advantageous in the coordination of multiple muscles.

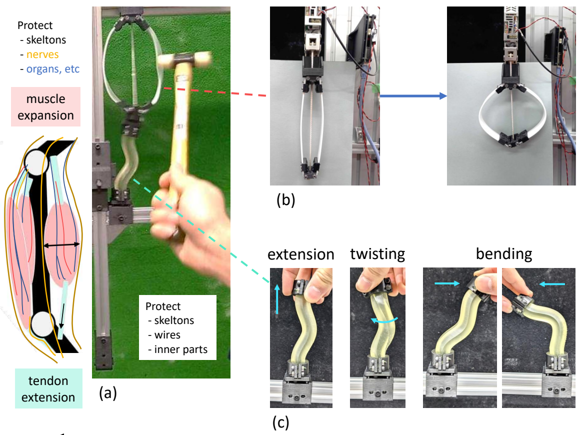

Figure 1: (a) Extensions of wire-drive based on MTC have internal protection functions. (b) The muscle-like exterior and contraction experiments. (c) Rubber tendons with various shapes store elastic energy in various deformations.

2.2 Rubber Tendons

As an elastic element combined with the contraction mechanism, a rubber tendon with a Shore hardness of 50 is fabricated by a stereolithography printer. Although there are some examples of research on mechanisms that combine wire drives with nonlinear elastic elements [5, 6], these are fixed at a point at the end and work only for extension in one direction. Rubber fabricated by stereolithography can be easily formed into various shapes, and by constraining the posture of the ends, it generates a restorative force against various deformations (Figure 1(c)). Furthermore, it can reflect the differences in properties caused by the differences in size and attachment traits found in tendons of animals.

3 Experiments and Discussions

In the following experiments, each element is loaded vertically upward by the muscle module [4], and the contraction length, contraction velocity, and tension can be measured. We consider that the deformation of the wire itself is negligible compared to the deformation of the exteriors.

3.1 Experiments on the Muscle Exterior

The width of the muscle exterior depends only on the contraction length (Figure 2(a)). When the current of the motor that winds the wire is increased or decreased, the mus-

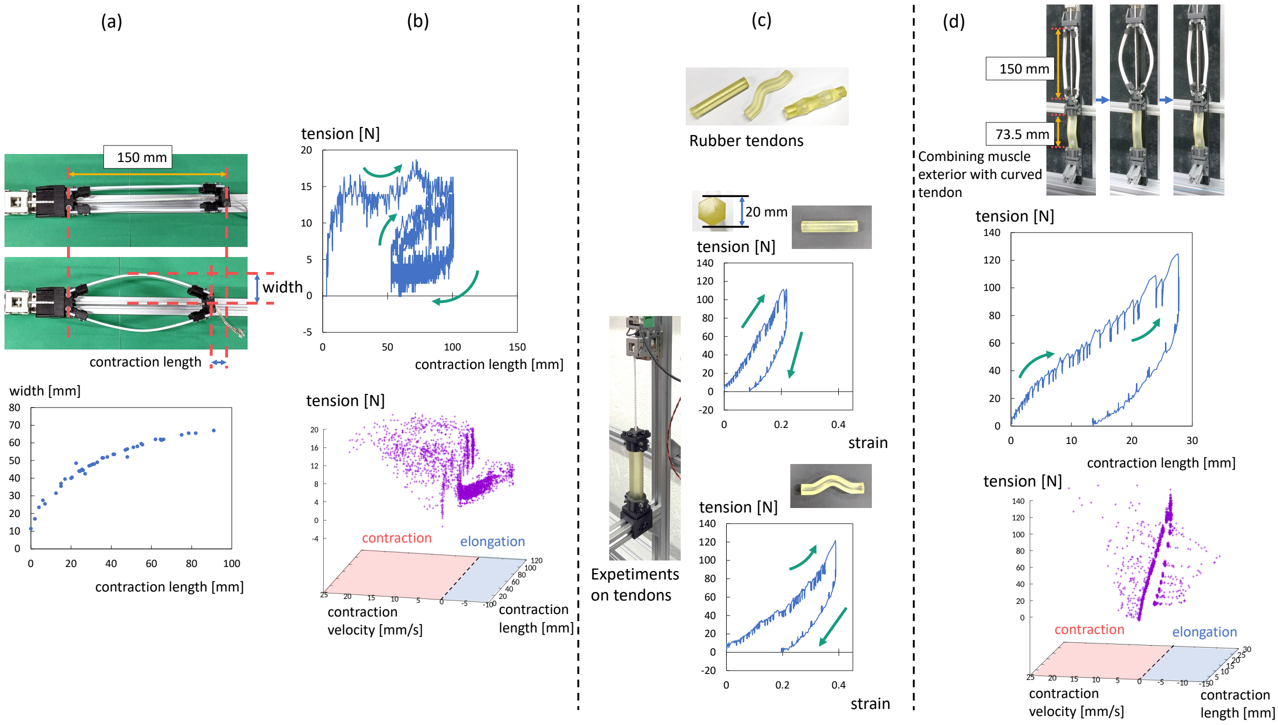

Figure 2: (a) Muscle exterior expands in response to contraction. (b) The relationship between tension, contraction length and contraction velocity in the contraction experiment (Figure 1(b)). (c) The relationship between tension and strain when increasing and decreasing the load applied to the linear tendon and curved tendon. (d) The relationship between tension, contraction length and contraction velocity in the experiment combining the muscle exterior and the curved tendon.

cle exterior shows a stable shape change after the restoring force increases or decreases during contraction from the initial posture (Figure 2(b)). As for the relationship with velocity, the muscle exterior generates a larger restoring force during contraction. Since this is the force against the wire, the force that can be exerted in combination with the wire drive becomes smaller during contraction, which is consistent with the tendency of muscles in animals [1].

3.2 Experiments on Tendons

Experiments were conducted on a linear tendon and a curved tendon by increasing and decreasing the load in steps (Figure 2(c)). It can be said that the nonlinear relationship between contraction length and tension can be obtained by changing the shape of the rubber. The hysteresis, which is considered to originate from the friction in the winding section, is a property that is not found in biological tendons and its treatment is a future issue.

3.3 Experiments Combining Muscle and Tendon

The properties of a structure combining muscle exterior and curved tendon were also investigated (Figure 2(d)). The combination with the tendon restores the shape of the muscle. The combination of the two properties leads to complex nonlinearity. On the other hand, there is no change in the properties depending on the contraction velocity.

4 Conclusions

In this study, we investigate the deformation and loading properties of a wire-driven structure that combines a muscle-like exterior and rubber tendons of various shapes. The parts of the muscle and tendon protect the wire and exhibit non-linearity. In the future, we will establish control methods to utilize the complex properties and design methods to achieve the desired properties. We will also use this structure to create a bio-mimetic robot that can perform a variety of motions.

References

[1] Ian E Brown, Stephen H Scott, and Gerald E Loeb. Mechanics of feline soleus: Ii design and validation of a mathematical model. *Journal of Muscle Research & Cell Motility*, 17:221–233, 1996.

[2] J. Yamaguchi and A. Takanishi. Development of a biped walking robot having antagonistic driven joints using nonlinear spring mechanism. In *Proceedings of International Conference on Robotics and Automation*, volume 1, pages 185–192 vol.1, 1997.

[3] Ryan M. Robinson, Curt S. Kothera, Robert M. Sanner, and Norman M. Wereley. Nonlinear control of robotic manipulators driven by pneumatic artificial muscles. *IEEE/ASME Transactions on Mechatronics*, 21(1):55–68, 2016.

[4] Yuki Asano, Toyotaka Kozuki, Soichi Ookubo, Koji Kawasaki, Takuma Shirai, Kohei Kimura, Kei Okada, and Masayuki Inaba. A sensor-driver integrated muscle module with high-tension measurability and flexibility for tendon-driven robots. In *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 5960–5965, 2015.

[5] K. Kawaharazuka, S. Makino, K. Tsuzuki, M. Onitsuka, Y. Nagamatsu, K. Shinjo, T. Makabe, Y. Asano, K. Okada, K. Kawasaki, and M. Inaba. Component Modularized Design of Musculoskeletal Humanoid Platform Musashi to Investigate Learning Control Systems. In *Proceedings of the 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 7294–7301, 2019.

[6] Kazuo Haiya, Satoshi Komada, and Junji Hirai. Tension control for tendon mechanisms by compensation of nonlinear spring characteristic equation error. In *2010 11th IEEE International Workshop on Advanced Motion Control (AMC)*, pages 42–47, 2010.