Paper:

Development and Application of High Contractile Pneumatic Artificial Muscle

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The purpose of this study is to develop a pneumatic artificial muscle with a high contractile rate to realize a required performance in a power assist device. The developed muscle is constructed with two nylon bands and an expansion unit. The generated force from the expansion unit is converted to a contraction force by the nylon band. This artificial muscle can be realized the high contractile rate. In this paper, the structure and the characteristics of the developed muscle are described, and then the application of this artificial muscle is discussed.

Keywords: pneumatic, artificial muscle, wearable robot, power assist wear

1. Introduction

The many power assist devices have been developed to assist a hard work, rehabilitate a human body in recent years [1–5]. These devices are driven with various actuators such as an electric motor, a hydraulic cylinder and so on. Above all, a pneumatic artificial muscle is effective to drive these devices [4, 5]. Since these devices used by a human is required a safety and a light weight. This actuator has a mechanical flexibility according to the air compressibility, a flexible material, and has a high power weight ratio. Therefore, this artificial muscle can realize a flexible and a light weight device with a simple mechanism.

McKibben-type pneumatic artificial rubber muscle (hereinafter McKibben-type rubber muscle) is often used as an actuator for the above device. McKibben-type rubber muscle has a simple structure and a high generated force. From these advantages, a power assist device using McKibben-type rubber muscle can realize a compact and a simple mechanism. However, this rubber muscle has a disadvantage, which has few contraction rates (about 30 %). In order to assist a human movement, an artificial muscle is required a high contractile rate.

The purpose of this study is to develop a high contractile pneumatic artificial muscle (hereinafter high contractile muscle). The developed muscle is constructed with nylon bands and an expansion unit. The generated force from the expansion unit is converted to a contraction force by the nylon band. The pleated pneumatic artificial muscle [6] which has also a high contraction rate has been developed. The developed muscle has clearance between the expansion unit and the end of the muscle. Therefore, the contraction rate can be designed easily by adjusting the initial length of muscle and the length of expansion unit. It is a strong point of this muscle compared with the above one that the contraction rate can be designed arbitrarily.

In this paper, the structure and the fundamental characteristics of the developed muscle are described, and then the applications of this muscle are discussed.

2. High Contractile Pneumatic Artificial Muscle

Figures 1 and **2** show a structure of a high contractile muscle. The developed muscle consists of nylon band A and an aluminum film balloon. The Depth and the thickness of nylon band A are 50, 0.6 mm, respectively. The aluminum film balloon as shown in **Fig. 3** is covered with a nylon band B (Width: 85 mm, Depth: 80 mm, Thickness: 0.6 mm). Aluminum film balloon is made by gluing outsides of two aluminum films. Therefore, this balloon can have 70 mm in inner width, 65 mm in inner depth. These balloons and nylon band A are sewn at the points shown as the solid black arrow in **Fig. 1**. These balloons are called an expansion unit hereafter.

Figure 4 shows an overview of this artificial muscle. When a compressed air is supplied into the balloons, the balloon as shown in **Fig. 3** expands to a height direction. Therefore, the expansion unit also expands to height direction. By constructing a pantograph mechanism by the nylon band, the displacement of the expansion unit can be converted to a contraction displacement as shown in **Fig. 4(b)**.

The contraction length (contraction rate) is easily adjusted by changing the sewing distance between both ends of this muscle as shown by solid black lines in **Fig. 2(b)**. The contraction rate is the rate of the contraction and initial lengths. It is an advantage of the developed muscle that the contraction rate can be adjusted easily. In this

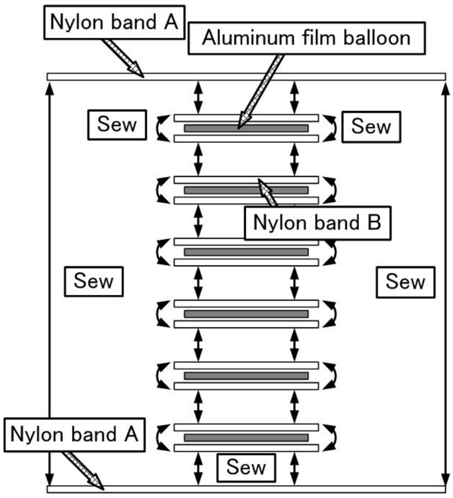
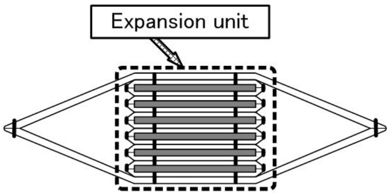
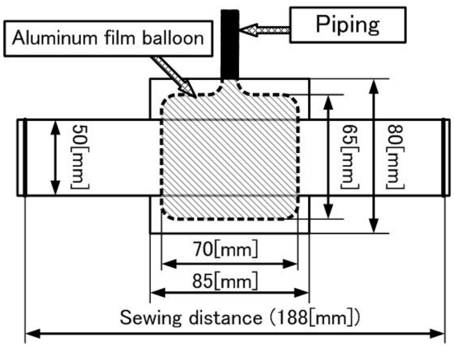


Fig. 1. Structure of developed artificial muscle.



(a) Side view



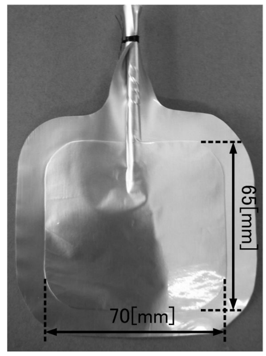
(b) Top view

Fig. 2. Side and top view of developed muscle.

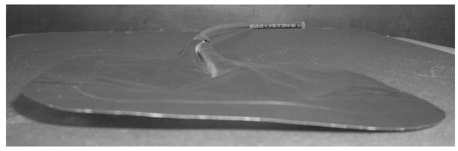
research, the sewing distance of 188 mm yields a contraction rate of 55%.

Figure 5 shows a force characteristic of the high contractile muscle. In this experiment, the artificial muscle is fixed at the initial state as shown in **Fig. 6**. The developed muscle is pressurized from 0 to 120 kPa. The contraction force is measured by a force sensor on a sensor stage. From the result, this artificial muscle can generate about 700 N at the initial length.

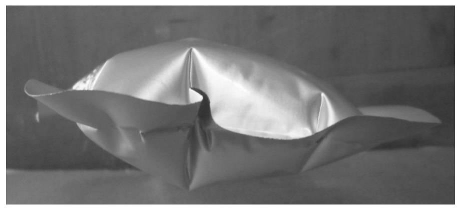
Characteristics of high contractile muscle and McKibben-type rubber muscle are measured to compare the developed muscle with a previous one. McKibben-type rubber muscle, as shown in **Fig. 7,** is 450 mm in length of a driven part and 10, 14 mm in inner and outer diameters of a rubber tube, respectively. The size of McKibben-type rubber muscle is decided to have almost same contraction force and length of the high contractile muscle.



(a) Top view

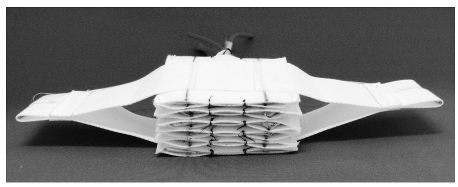


(b) Side view (Initial state)

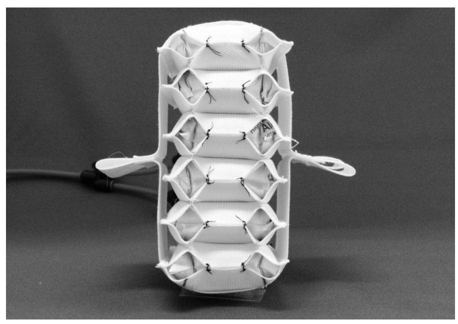


(c) Side view (Pressurized state)

Fig. 3. Overview of aluminum film balloon.



(a) Initial state



(b) Pressurized state

Fig. 4. Overview of developed artificial muscle.

In this experiment, the rubber muscle is also fixed to the sensor stage as shown in **Fig. 6**. The contraction force is also measured by a force sensor attached with a sensor stage. The contraction length is measured by a linear encoder attached with a sensor stage.

As shown in **Figs. 8(a)**, **(b)** and **(c)**, the developed muscle has almost same maximum contraction force and length at 90 kPa. In addition, it is confirmed that the required inner pressure of the high contractile muscle is lower than McKibben-type rubber muscle, and the designed contraction rate (55%) can be almost realized.

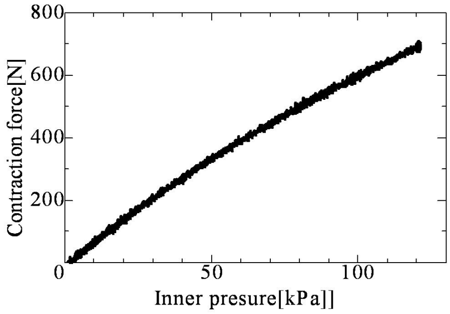


Fig. 5. Force characteristic at initial state.

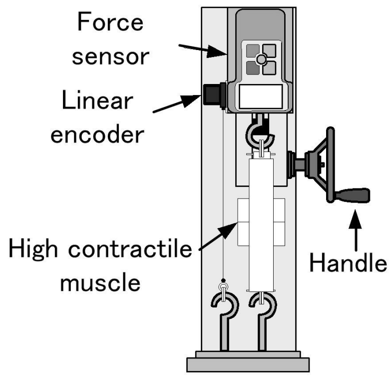
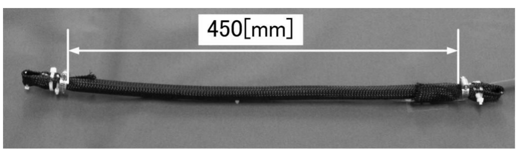
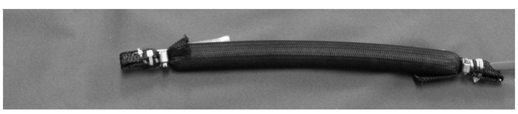


Fig. 6. Experimental setup to measure a force characteristic.

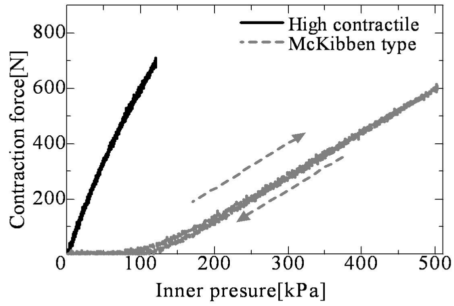


(a) Initial state

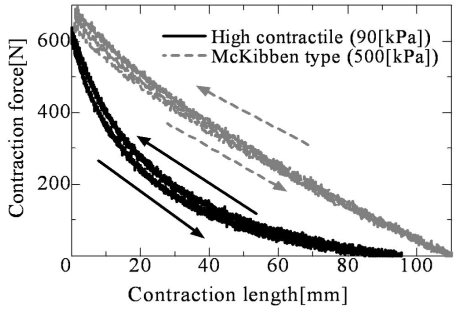


(b) Pressurized state

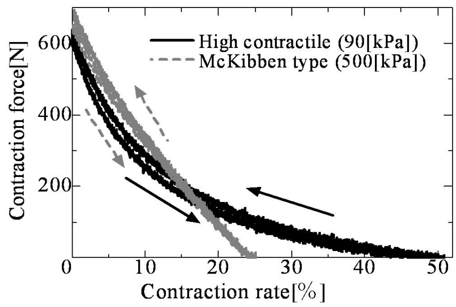
Fig. 7. Over view of McKibben-type rubber muscle.



(a) Force characteristic at initial state



(b) Relation between contraction length and force



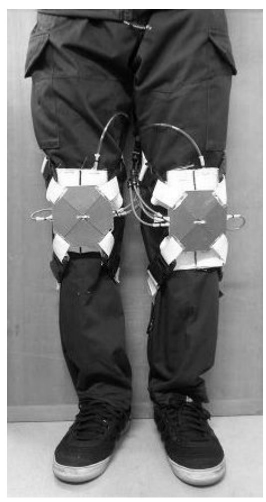
(c) Relation between contraction rate and force

Fig. 8. Comparison with McKibben-type rubber muscle.

3. Application of Developed Artificial Muscle

A power assist wear for a knee is developed as an application of the developed muscle. Overview of the developed device is shown in **Fig. 9**. This device consists of artificial muscles and trousers as shown in **Fig. 10**. Nylon bands from the artificial muscle are fixed on back of the thigh and calf through adjuster buckles. This device can reduce a human weight load without a link mechanism. In addition, a human can use this device easily because they just wear trousers. These are the strong points of the developed assist wear.

If an actuator is put parallel to a human body without a link mechanism, an assist force from an actuator is also applied parallel to a human body. This parallel applied force can reduce load. However, a human joint is also applied an axial force by an actuator. Therefore, it is desirable that an actuator applies a vertical assist force to a human body in order to protect a knee joint from an excessive axial force.



(a) Front view

(b) Side view

Fig. 9. Overview of power assist wear (Pressurized state).

The artificial muscle is modified as shown in **Fig. 11** for increasing a vertical force to a human body. This muscle consists of the expansion unit, nylon bands and metal

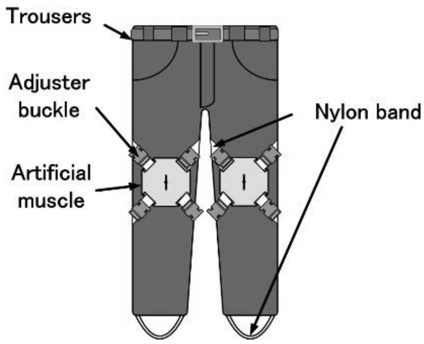
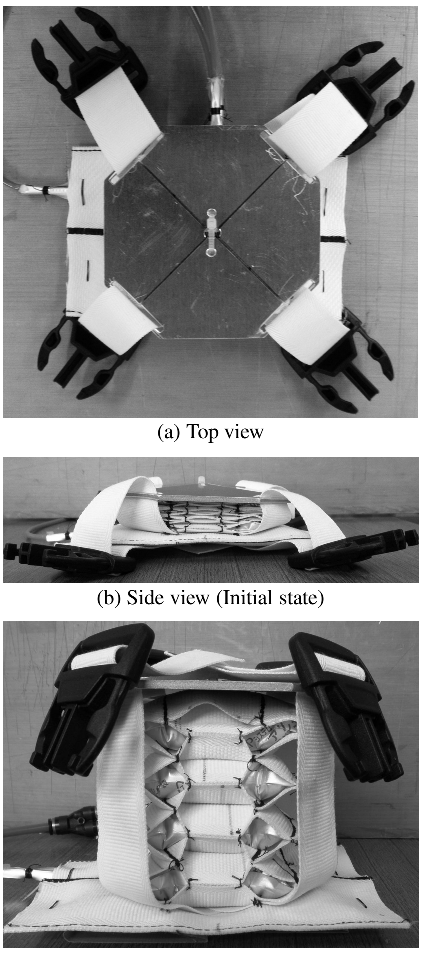


Fig. 10. Structure of power assist wear.



(a) Top view

(b) Side view (Initial state)

(c) Side view (Pressurized state)

Fig. 11. Overview of modified artificial muscle.

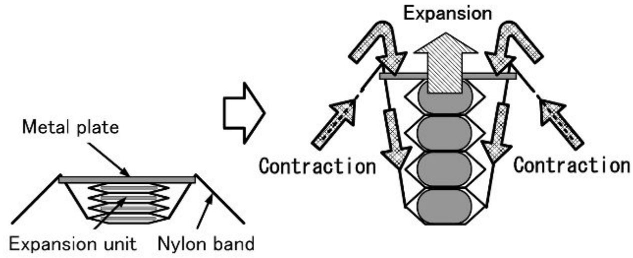


Fig. 12. Structure and principle of operation.

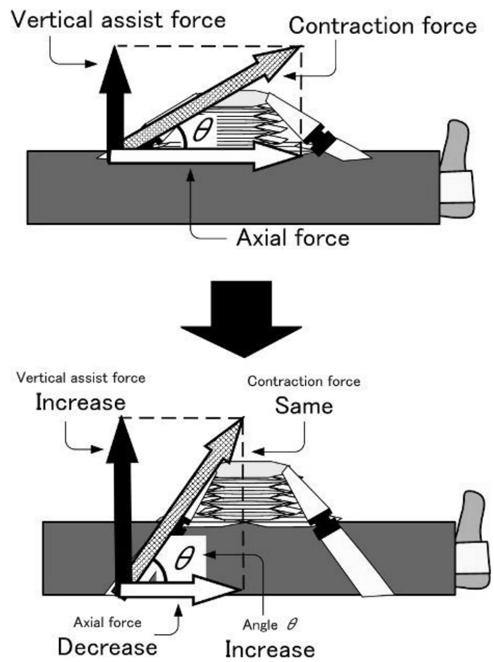


Fig. 13. Principle of assist.

plate and adjuster buckles. The expansion unit has four aluminum films, which has the same size unit shown in **Fig. 2**. One end of the band is fixed to the bottom of the expansion unit as shown in **Fig. 11(b)**. The metal plate on the expansion unit is threaded on the other end of the nylon band.

The metal plate plays a movable pulley in this muscle. Therefore, when the compressed air is supplied into the expansion unit, the nylon band is pulled into the unit side with the displacement of the metal plate as shown in **Fig. 12**. The expansion force is converted to the contraction force along the length direction of the nylon band. The vertical assist force can be increased as shown in **Fig. 13** since the angle θ between the nylon band and the human body is increased by fixing the nylon band on back sides of the thigh and calf.

A generated torque is measured to verify a fundamental performance. **Fig. 14(a)** shows an outline of measurement. In this experiment, the developed device which includes trousers is put on a mannequin. A constant pressure (50 kPa) is supplied into the artificial muscle. The mannequin is flexed by a force sensor, and the generated torque is calculated from the force and the moment arm. The mannequin is moved horizontally with the ground in order to remove the effect of the gravity. The mannequin is flexed from 0° to about 45°. The flexion force is decreased slowly after the angle is arrival at 45°. The knee angle is measured with an angle sensor.

Figure 14(b) shows the torque generated at 50 kPa. Hysteresis occurs due to friction between the metal plate and nylon band. However, the torque can be generated about 14 Nm at maximum. Torque required per leg for an average Japanese man weighting 63 kg is calculated to be about 34 Nm to maintain a 45° angle. This device is expected to assist about 41% of weight torque at 45°.

An assist performance is verified when a subject wears

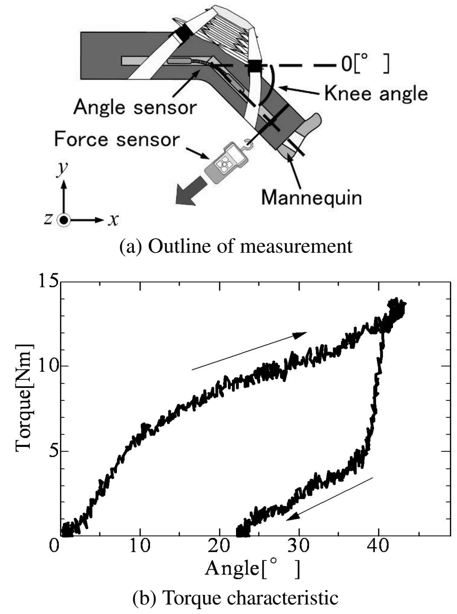


Fig. 14. Generated torque characteristic.

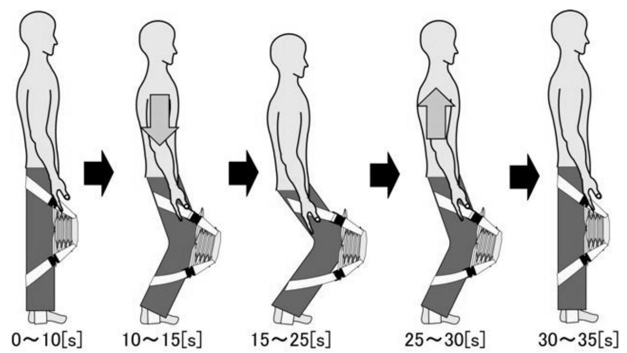


Fig. 15. Movement for subject to verify the assist performance.

this device. In the experiment, subject moves as follows and shown in **Fig. 15**:

0–10 s: Stands straight.
10–15 s: Flexes the knee to 50°, 70°, 90°.
15–25 s: Maintains the knee angle.
25–30 s: Extends the knee to 0°.
30–35 s: Stands straight.

EMG is measured at the rectus femoris muscle with and without the assist. EMG amplitude is increased when the muscle generates contraction force. IEMG is shown in **Figs. 16**, **17** and **18**. IEMG, an index of muscle activity, is calculated based on the moving average of the absolute value of EMG. IEMG increases when the muscle generates the contraction force to balance the weight load.

From the figures, this device is most effective at 50° to reduce the weight load because IEMG decreases when the subject flexes the knee at 50°. The vertical assist force shown in **Fig. 13** decreases with increasing knee angle. Therefore, the effect to reduce the weight load decreases with increasing knee angle compared to the effect at 50°. However, IEMG with assist can also be decreased at 70° and 90° compared to IEMG without assist.

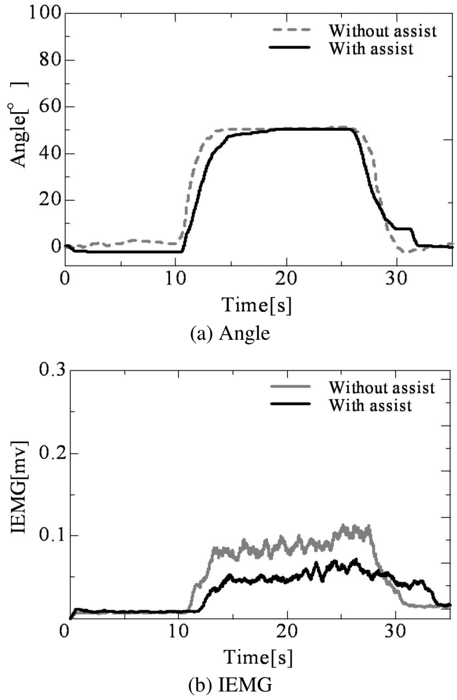


Fig. 16. Verification of assist performance (50°).

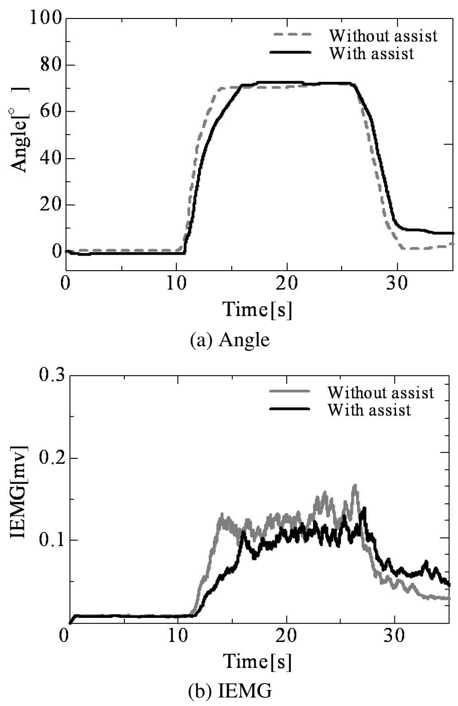
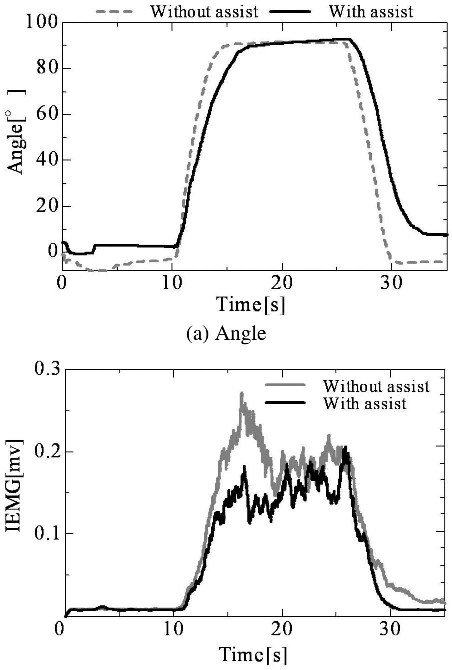


Fig. 17. Verification of assist performance (70°).

4. Conclusion

In this paper, the structure and the characteristics of the high contractile muscle have been described, and then the power assist wear have been discussed as the application of the developed artificial muscle.

It has been confirmed from the experiments that the high contraction rate and the designed contraction rate (55%) have been almost realized. In addition, the link-less



(a) Angle

(b) IEMG

Fig. 18. Verification of assist performance (90°).

mechanism for the power assist wear have been realized by using this artificial muscle.

One problem remaining is that the contracted muscle volume of this muscle exceeds that of McKibben-type rubber muscle. Solving this problem remains for future work.

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