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New concept and fundamental experiments of a smart pneumatic artificial muscle with a conductive fiber

Shuichi Wakimoto[a,*], Jumpei Misumi[a], Koichi Suzumori[b]

[a] Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima-naka, Kita-ku, Okayama 700-8530, Japan
[b] Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

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ABSTRACT

A McKibben artificial muscle consisting of a rubber tube and a mesh sleeve made from fibers is a promising actuator as an artificial muscle because of its high power, low weight, and flexibility. However, an external pressure sensor or an expensive electro/pneumatic regulator is generally required to control the pneumatic pressure to drive the actuator.

A novel smart McKibben-type artificial muscle with a pressure-sensing function has been proposed and developed in this study. One fiber on the sleeve of the actuator is converted from a normal to a conductive material. The applied pressure is estimated by observing the electrical resistance of the conductive fiber. Therefore, the fiber works as both a sensor and an actuator element.

The fabrication process of the smart artificial muscle is established in this report, and the basic characteristics are clarified. Moreover, a compact driving control system of the smart artificial muscle, which uses a small rotary pump without external sensors, electro/pneumatic regulator, or valves, is proposed.

1. Introduction

Various wearable apparatuses, such as a power-assist device for supporting human movement and a rehabilitation apparatus for supporting a care receiver's independence, have been developed in the medical and welfare fields. Some of these devices are designed to be attached to the human body; hence, high safety is required. A McKibben artificial muscle, which is configured with a rubber tube and a fiber sleeve covering the tube and axially generates contraction displacement, is often used in such mechanisms because of its flexibility and low weight that lead to high safety [1–7].

The McKibben artificial muscle itself is light and flexible. However, the servo control system that drives the artificial muscle generally tends to be bulky, rigid, heavy, and expensive because it includes an air compressor, external sensors, and an electro/pneumatic regulator. Therefore, reducing the size and weight of the control system, which improves the usability of the McKibben artificial muscle, is highly expected. The sensing mechanism attaching directly on the artificial muscle have been investigated from this demand. Hamamoto et al. developed a flexible potentiometer for sensing the displacement using a conductive fiber and mounted it on the artificial muscle surface [8]. Olympus Corp. proposed the sensing mechanism using a potentiometer. The potentiometer was inserted inside a rubber tube [9]. Akagi et al. incorporated a photo displacement sensor in the McKibben artificial muscle by measuring the expansion quantity in the radial direction by the sensor. They also estimated the displacement in the axial direction [10]. Park et al. used a conductive fluid. They made a spiral channel on the rubber tube of the artificial muscle and enclosed the fluid in the channel. The displacement of the artificial muscle was obtained by measuring the electrical resistance [11]. Aiming at an active supporter for human walking, Park and Wood fabricated an elastomer strain sensor and made a sensor-artificial muscle unit. The elastomer sensor can detect the artificial muscle deformation [12]. Oki et al. mounted a strain gage on an artificial muscle. The strain gage can detect the muscle deformation, and the contracting displacement can then be calculated [13]. Kuriyama et al. developed a flexible electro-conductive rubber sensor for measuring the displacement of the artificial muscle. The sensor obtained a circumference length, and the axial displacement was found [14]. Wakimoto, who is one of the authors of the present paper, and colleagues incorporated a soft rubber sensor into the McKibben artificial muscle. The rubber sensor had a conductive film. The displacement of the artificial muscle was found by measuring the electrical resistance [15]. Yonekura and Kuniyoshi proposed an embedded eddy current sensor, which obtained displacements

* Corresponding author.
E-mail address: wakimoto@okayama-u.ac.jp (S. Wakimoto).

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by measuring the rubber tube thickness [16]. Goulbourne et al. developed a self-sensing artificial muscle using dielectric elastomer sensors. The sensor made contact with the inner artificial muscle surface. The electrical signals from the sensor then changed with the artificial muscle deformation [17].

Many bodies of research on the pneumatic smart artificial muscle have focused on the addition of a displacement sensor element to the artificial muscle. These mechanisms do not employ external displacement sensors and show high potential for realizing small displacement controlling systems (i.e., systems without rigid and large conventional displacement sensors). However, in general the system is still required to have pneumatic pressure sensing/controlling devices. This is because the pressure must be adjusted for servo displacement control. Additionally pressure information is essential for estimating generative force during servo displacement control. The pressure sensing/controlling devices, examples are a pressure sensor, an analog valve and an electro-pneumatic regulator, are generally expensive, rigid, heavy, or large in size compared to an artificial muscle.

We solve the abovementioned problems herein by developing a smart McKibben artificial muscle with a pressure-sensing function through a very easy fabrication process. In our artificial muscle, a conductive fiber is used as the sleeve. The fiber works as both essential element for actuation and the pressure sensor. Therefore, the additional pressure-sensing element is not required. Furthermore, pressure control can be achieved using a small tubing pump with a direct current (DC) motor. The artificial muscle structure is similar to the general McKibben artificial muscle. Therefore, combining the abovementioned embedded displacement sensors will be easy, then the small, light, and inexpensive displacement control system with estimating function of generative force will be realized in the future.

The concept and the fabrication process for our smart artificial muscle are introduced first in this paper. The fundamental characteristics of the electrical resistance of the conductive fiber against the applied pressure are then experimentally measured. A simple control system using a tubing pump is established after which, and the pressure servo control of the artificial muscle is achieved. The conclusion and future plans are finally mentioned.

2. Smart artificial muscle concept

2.1. Driving principle and fabrication process for the McKibben artificial muscle

Fig. 1 illustrates the structure and driving principle of the McKibben artificial muscle. The artificial muscle consists of a rubber tube working as an air chamber, a sleeve made of knitted fibers with a mesh form, and an air supply tube. The rubber tube is covered by the sleeve. One end of the tube is blocked, while the other has the air supply tube. The rubber tube expands in the radial direction by applying a positive pneumatic pressure. At the same time, the angle of the fibers changes from θ_0 to θ_1. The contraction force and displacement are generated in the axial direction because the fibers work as a pantograph mechanism (Fig. 1).

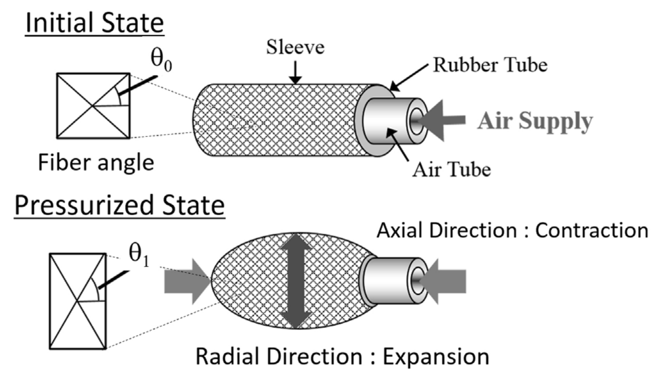

Fig. 1. Structure and driving principle of the McKibben artificial muscle.

In general, the rubber tube and the sleeve are separately fabricated. The McKibben artificial muscle is then made by inserting the rubber tube into the sleeve. An easier process of making the McKibben artificial muscle can be established using a braider machine generally used for making a twisting string. Fig. 2 shows the braider machine mainly comprising multiple bobbins with fibers and a winding roller. The half numbers of the bobbins rotate in a clockwise direction, while the others turn in a counter-clockwise direction following the ditch by an electrical motor (Fig. 2). All fibers from the bobbins are then twisted by crossing each other at the top center of the machine for making a mesh sleeve. A rubber tube is set in the center of the twisted fibers to automatically pull them up together using the winding roller, provided that the tube is covered by the mesh sleeve [18,19]. Both ends of the sleeve and the rubber tube are then adhered. The air supply tube is attached, and the artificial muscle is then accomplished. The relative position and the spiral shape of the fibers can be kept correctly without mechanical support or special fixing techniques. Only the knitting angle of the fibers is changed when the actuator axially contracts and radially inflates.

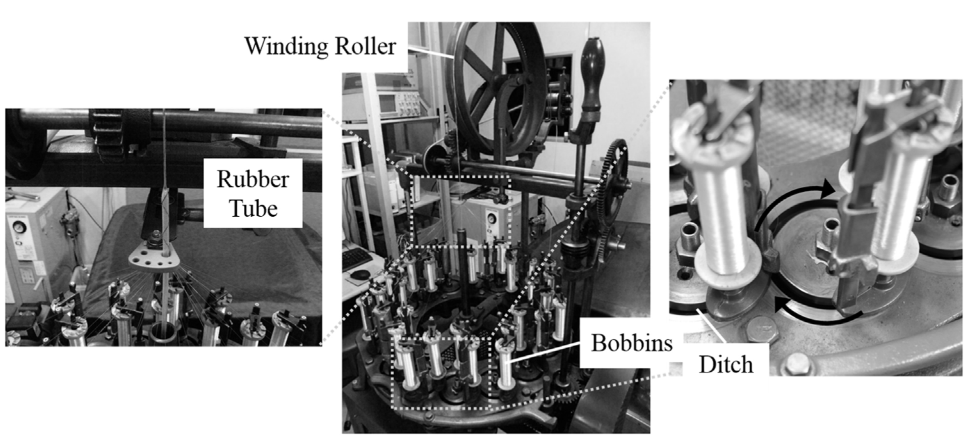

Fig. 2. Fabrication of the McKibben artificial muscle by the braider.