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Time-Lag Generation Mechanical Valve for Enhancing Time Response of Back-Stretchable McKibben Muscles

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***Abstract*— McKibben artificial muscles are capable of contracting when pneumatic pressure is applied. However, they face difficulties in passively elongating from their natural length due to external forces when not pressurized. This limitation poses challenges in systems where artificial muscles interact, such as in antagonistic drive configurations. To address this issue, we have so far developed a novel type of McKibben artificial muscle called the back-stretchable McKibben muscle (BSM). The BSM consists of two primary sections: a contraction section and an elongation section. An inlet tube is inserted between these two sections to restrict airflow. This design enables the elongation section to activate prior to the contraction motion of the contraction section. While this sequential operation allows the BSM to be used in antagonistic drive systems, a new challenge emerged: the restricted airflow resulted in slower response times of the BSM. To address this issue, this paper proposes a mechanical valve called the "Time-lag generation mechanical valve (TLV)," which generates a time lag in air inflow to the sections without using an inlet tube. Experimental results demonstrate that incorporating the TLV into the BSM significantly enhances its time response: by approximately 300 times during contraction and approximately 230 times during pressure release. Furthermore, the integration of TLV-equipped BSMs enabled the successful implementation of object throwing in an antagonistic drive robotic arm, a feat previously unattainable with conventional BSMs.**

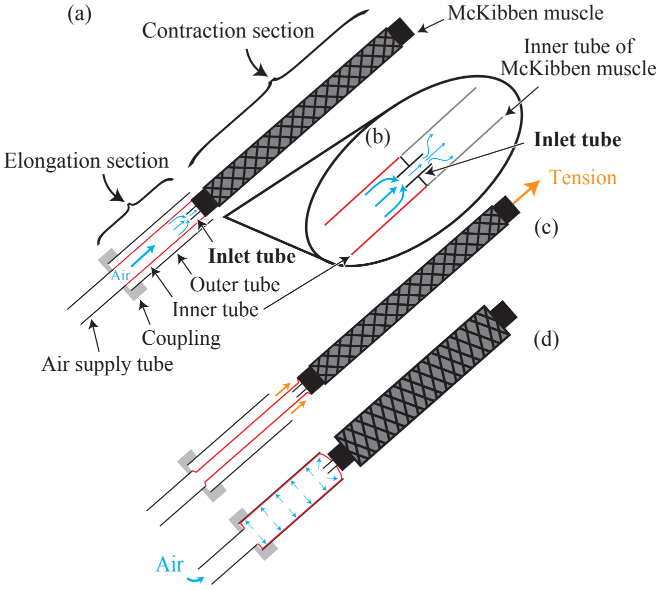

Fig. 1. (a) Structure of the BSM. (b) Air flow into the inlet tube. (c) Back-stretching state, where the elongation section is stretched. (d) Contracting state, where the elongation section locks.

I. INTRODUCTION

Various artificial muscles have been developed to mimic the contractile function of natural muscles [1]–[6]. Among these, the McKibben artificial muscle is the most widely used and representative [7]–[9]. The McKibben artificial muscle consists of a rubber tube encased in a braided sleeve structure, which generates contractile force when pneumatic pressure is applied to the rubber tube. However, while McKibben artificial muscles can contract when pneumatic pressure is applied, they face difficulties in passively elongating from their natural length due to external forces when not pressurized [10]. This limitation poses challenges in systems where artificial muscles interact, such as in the musculoskeletal robots we have developed [11], [12]. To address this issue, our robots utilized longer artificial muscles, installed with intentional slack. However, this installation method does not fully utilize the maximum contraction capacity of the artificial muscles. Therefore, we proposed a new type of McKibben artificial muscle called the "Back-stretchable McKibben muscle (BSM)" [13]. The BSM is capable of not only contracting when pneumatic pressure is applied but also passively elongating from its natural length due to external forces when not pressurized (back-stretching).

As shown in Fig. 1(a), the BSM consists of a contraction section that enables contraction and an elongation section that facilitates back-stretching. During non-pressurized states, the soft inner tube in the elongation section can stretch, allowing for back-stretching (Fig. 1(c)). When pressurized, the inner tube expands, creating friction with the outer tube, which locks the elongation section, while simultaneously the contraction section contracts (Fig. 1(d)). As illustrated in Fig. 1(b), an inlet tube is inserted between these sections to restrict airflow to the contraction section. This design ensures that when pressure is applied, the elongation section locks first, followed by the activation of the contraction section. Without the inlet tube creating this time lag, the BSM would not function effectively to increase the antagonistic drive range in antagonistic configurations. However, the reduced airflow to the contraction section caused by the inlet tube resulted in slower response times when the BSM was pressurized [14]. Consequently, the BSM proposed in [13] was unable to perform tasks requiring rapid movements, such as throwing objects, when actuating robotic arms. To address this issue, this paper proposes a

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TABLE I

TIME RESPONSE OF BSM AND CONVENTIONAL THIN MCKIBBEN MUSCLES WHEN AIR PRESSURE IS SUPPLIED AND RELEASED.

	BSM	thin McKibben
Air pressure supply	30 s	0.07 s
Air pressure release	70 s	0.1 s

mechanism that maintains the sequential operation of the elongation section locking before the contraction section activates, even after removing the inlet tube, thereby improving the BSM's time response. While optimizing the inlet tube diameter could potentially enhance time response, the inlet tube continually restricts airflow, even after the elongation section is locked, preventing the full realization of the BSM's potential. Therefore, we propose a mechanism to operate the BSM without utilizing flow restriction through an inlet tube.

The structure of the remaining sections of this paper is as follows. First, in Section II, we quantitatively elucidate the time response issues of the BSM proposed in [13] through comparison with conventional McKibben muscles. Section III describes the structure and manufacturing method of the proposed mechanism, as well as its time response characteristics when applied to the BSM. Subsequently, in Section III, we apply the BSM equipped with the time response improvement mechanism to a robotic arm and verify its effectiveness. Finally, we present our conclusions and discuss future prospects.

II. TIME RESPONSE OF BACK-STRETCHABLE MCKIBBEN MUSCLES

To elucidate the time response issues of the BSM proposed in [13], we replicated the experiment described in [14], using a conventional thin artificial muscle (with the same dimensions as the BSM used in [14]). We applied $0.4\ \mathrm{MPa}$ of pneumatic pressure and tracked the muscle's movement during pressure supply and release using video footage. The change in contraction ratio over time was measured and compared with the results obtained for the BSM in [14]. The results are presented in Table I, which illustrates, for the contraction motion, the time required for the artificial muscle's movement to reach $90\ \%$ of its final value from the onset of motion. As shown in Table I, the BSM requires 30 seconds for contraction due to the influence of the inlet tube, whereas the thin artificial muscle contracts instantaneously in 0.07 seconds. Additionally, Table I demonstrates that, due to the effect of the inlet tube, the time required for pressure release is longer than that for pressurization, while the thin artificial muscle completes its action in 0.1 seconds. The significant difference shown in Table I arises because the inlet tube continues to restrict the flow rate even after sequencing the operation of the BSM. Therefore, if a mechanism were devised to create a time lag in the operation timing between the elongation section and contraction section without using an inlet tube, it might be possible to achieve a rapid time response of the BSM, similar to that of thin artificial muscles.

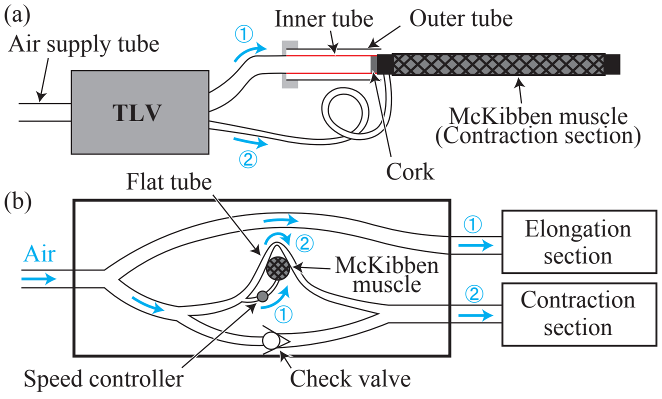

Fig. 2. Conceptional diagram of TLV. (a) How to conncet to the BSM. (b) Structure of TLV.

Although the BSM is divided into two sections, the contraction section and the elongation section, it functions as a single actuator. Therefore, a single input to the BSM is desirable. To address this, we propose a mechanical valve called the "Time-Lag Generation Mechanical Valve (TLV)," which creates a time lag between the airflow into the contraction section and the elongation section using a simple pneumatic single input without the need for active control. By incorporating this time-lag generating TLV into the BSM, it becomes possible to first activate the elongation section and subsequently activate the contraction section.

III. TIME-LAG GENERATION MECHANICAL VALVE

A. Structure and Working Principle

Fig. 2 illustrates the structure of the TLV. As shown in Fig. 2(a), pneumatic pressure is supplied through a single input port, passes through the TLV, and connects separately to the contraction section and the elongation section. It is important to note that, unlike the BSM in [13], the flow paths of the contraction section and the elongation section are not interconnected, and there is no inlet tube inserted. The internal structure of the TLV is depicted in Fig. 2(b). When pneumatic pressure is applied from the air supply tube, it first flows to the elongation section. Simultaneously, air is supplied to a McKibben artificial muscle within the TLV. This internal McKibben artificial muscle can be utilized as a trigger to alter the flow path in the mechanical valve [15]. At this stage, air does not flow through the Flat Tube (FT) [16]–[18], which is a flattened and bent section of the air supply tube, and the check valve. This is due to the buckling point created when the air tube is bent, which prevents air passage. As the McKibben artificial muscle within the TLV contracts and expands radially, it increases the bending radius of the FT, resolving the buckling point and allowing air to pass through. Consequently, air reaches the contraction section with a delay. The air supply tube connected to the contraction section is made sufficiently long to allow the BSM to back-stretch. The time lag generated by the TLV can be arbitrarily adjusted using a speed controller installed immediately before the McKibben artificial muscle, which

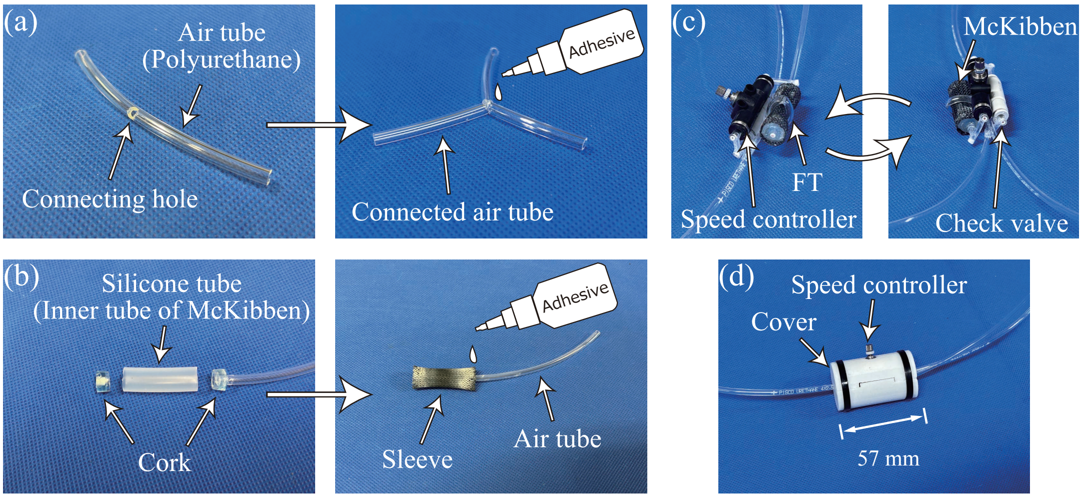

Fig. 3. Fabrication process of TLV. (a) How to make the air tube connecting point. (b) How to make the short McKibben muscle. (c) Internal structure of TLV. (d) Completed TLV.

regulates the airflow velocity. When the pneumatic pressure supply from the air supply tube is discontinued, the air in the contraction section is instantly released through the check valve.

B. Fabrication

Fig. 3 illustrates the fabrication method of the TLV. As shown in Fig. 3(a), the branching air pathways that constitute the TLV were created by drilling holes in the side of polyurethane tubes and adhering the branching tubes. This method allows for significant miniaturization of the pathways compared to using commercial one-touch fittings. The tubes composing the TLV have outer diameters of $3\ \mathrm{mm}$ and $4\ \mathrm{mm}$, with inner diameters of $2\ \mathrm{mm}$ and $2.5\ \mathrm{mm}$, respectively. As depicted in Fig. 3(b), the McKibben artificial muscle inserted into the TLV was fabricated using commercial silicone tubing (outer diameter $10\ \mathrm{mm}$, inner diameter $8\ \mathrm{mm}$) and commercial polyester braided tubing, rather than a thin artificial muscle. The radial expansion of this larger diameter McKibben artificial muscle enables the resolution of the buckling point in the FT, created by bending the tube with an outer diameter of $4\ \mathrm{mm}$ and an inner diameter of $2.5\ \mathrm{mm}$, allowing air to pass through. Instant adhesive (LOCTITE 401, Henkel AG & Co. KGaA) was used to connect the various components. The check valve used was CVPU4-4 (PISCO), and the speed controller was JSMU4 (PISCO). The TLV components were connected as shown in Fig. 3(c) and enclosed in a 3D-printed cover as illustrated in Fig. 3(d). The completed TLV measures $57\ \mathrm{mm}$ in total length and $33\ \mathrm{mm}$ in diameter, successfully achieving a compact design. Fig. 4 shows the fabricated TLV connected to the air pathways of a BSM constructed with the same dimensions as in [13]. However, unlike [13], no inlet tube was inserted, and each section of the BSM was plugged to ensure the pathways were not interconnected.

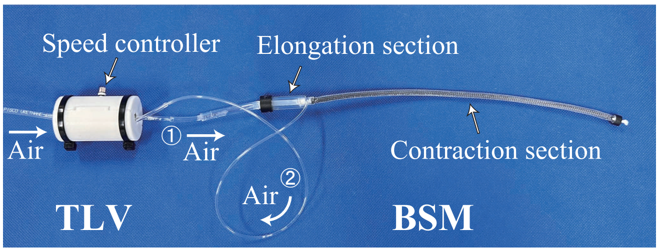

Fig. 4. Back-stretchable McKibben muscle with TLV.

IV. TLV APPLICATION TO BSM

A. Time response of BSM with TLV

To verify the effect of TLV on the time response of BSM, we measured the relationship between time and contraction ratio of the BSM connected to the TLV. Similar to the procedure in Section II, we applied $0.4\ \mathrm{MPa}$ of pneumatic pressure to the fabricated TLV and tracked the movement of the BSM during pressure supply and release using video footage. The results are presented in Fig. 5. The speed controller of the TLV was adjusted to minimize the time lag between the sequential activation of each BSM section while still maintaining the desired order of operation. As shown in Fig. 5(a), the BSM using TLV requires approximately 0.1 seconds to reach $90\ \%$ of its final value from the onset of motion for contraction. Fig. 5(b) illustrates that it takes approximately 0.3 seconds for pressure release. Considering that the time response of the BSM fabricated in [13] is as shown in Table I, these results indicate that the operation speed has improved by approximately 300 times during contraction and approximately 230 times during pressure release. These findings demonstrate that the time response of the BSM has been significantly enhanced through the use of TLV.

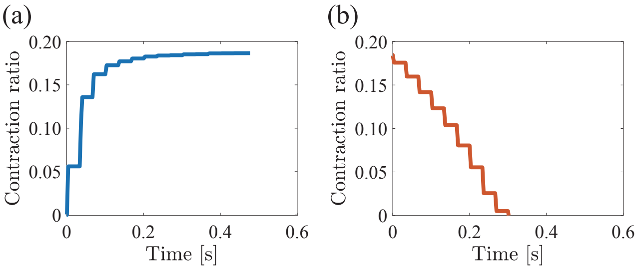

Fig. 5. Time response of the BSM with the TLV. (a) When air pressure is supplied. (b) When air pressure is released.

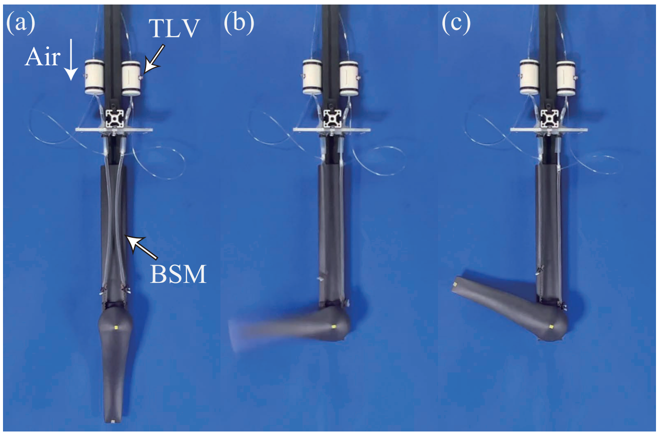

Fig. 6. Driving experiment using BSMs with TLVs. (a) Initial state. (b) Midway. (c) Max rotation angle.

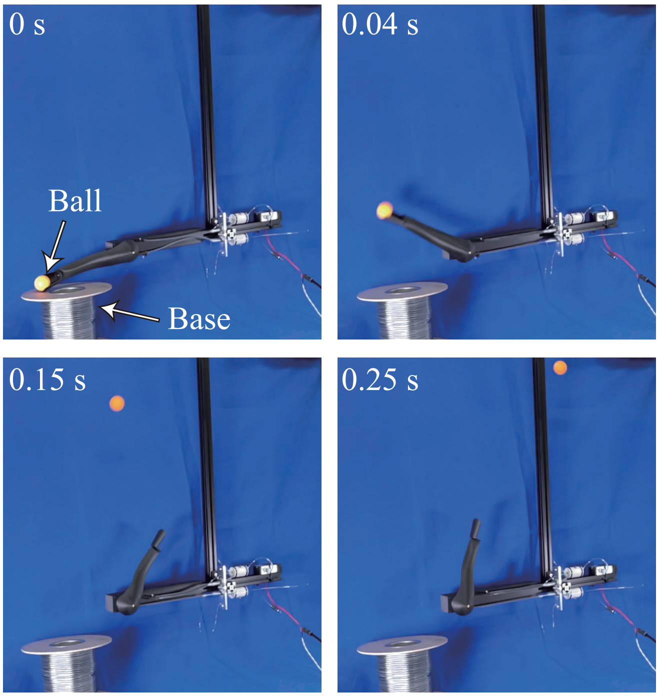

Fig. 7. Experiment of throwing a ping-pong ball.

B. *Robotic Arm using BSM with TLV*

To verify whether the BSM using TLV could improve the antagonistic drive range compared to conventional McKibben artificial muscles, as demonstrated by the BSM proposed in [13], we conducted experiments using the identical robotic arm, setup conditions, and BSM dimensions as those employed in [13]. The results are presented in Fig. 6. As illustrated in Fig. 6, the BSM utilizing TLV was successfully installed on the robotic arm without slack and effectively actuated the arm. The rotation angle of the robotic arm, shown in Fig. 6(c), was measured at 113 deg. Considering that the conventional McKibben artificial muscles achieved a rotation of 85.9 deg in [13], these results indicate that the BSM with TLV maintains its effectiveness in enhancing performance. The discrepancy in maximum rotation angle between this experiment and the BSM used in the robotic arm in [13] (which achieved a maximum rotation angle of 105 deg) can likely be attributed to manufacturing variations and inertial effects due to differences in rotation speed.

Furthermore, to demonstrate the improved time response of the BSM utilizing TLV, we conducted an experiment using the same robotic arm to throw a ping pong ball (weight: 2.7 g, diameter: 40 mm). The experimental setup and results are illustrated in Fig. 7. A small holder was attached to the end of the robotic arm to support the ping pong ball for the throwing action. As shown in Fig. 7, the BSM equipped with TLV successfully performed the ball-throwing motion, a task that was unattainable with the BSM fabricated in [13] due to its slower time response. This achievement demonstrates an enhancement in the practical applicability of the BSM and validates the effectiveness of the TLV-based approach.

V. CONCLUSION

In this study, we proposed a mechanical valve (TLV) to improve the time response of the BSM. This valve creates a time lag between the airflow into the contraction section and the elongation section of the BSM using a single pneumatic input. The TLV employs Flat Tubes (FT), check valves, and the radial expansion of McKibben artificial muscles to mechanically generate a time lag without the need for active control. By incorporating this mechanism into the BSM's actuation system, we successfully enhanced the BSM's time response, achieving approximately 300 times faster operation during contraction and approximately 230 times faster during pressure release. Furthermore, we experimentally demonstrated that a BSM equipped with this TLV enables an antagonistic drive robotic arm to perform throwing motions, which was previously unattainable.

In the future, we plan to apply the BSM with its enhanced time response to musculoskeletal robots, aiming to realize systems with a larger range of motion compared to conventional designs.

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