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ORIGINAL ARTICLE

Segmentation of a Soft Body and its Bending Performance using Thin McKibben Muscle

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ABSTRACT – In recent years, the soft actuator has been extensively developed in robotic research. This type of robot is expected to work with human due to its excellent performance while it is lightweight, has higher power output, flexibility, and adaptability advantages. Due to this factor, thin McKibben muscle actuator is of interest as an actuator for this research for bending application. Current study on actuator mainly focused on the new method of design, modelling, and control by manipulating shape, material, and braided for bending performance, and it is rarely studied on the optimisation of existing technology which could also give high performance with low-cost and time. This paper presents the segmentation of a soft body and its bending performance using thin McKibben muscle. Herein, we report a soft body using thin McKibben muscle actuator integrated with knitted thread as the pulley. The knitted point was used to divide the length of the actuator into a variant of length segment. This segment length technique was able to produce high bending angle output of 42º compared to the unsegmented length of 40º, increasing 1.0 times to the original value.

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INTRODUCTION

Recently, the soft actuator is one of the promising technologies with some remarkable achievements in bio-robotics [1], medical applications [2], wearable devices [3] and industrial applications [4]. Soft actuator offers safer robotics structure, lightweight, high flexibility and high power to weight ratio compared to traditional robotics [5,6]. One of the remarkable soft actuator inventions was McKibben Pneumatic artificial muscle [7,8]. McKibben actuator mechanism works in a simple method where a tube-like actuator is characterised by a decrement in length once pressurised [7] that converts pneumatic pressure to pulling force. It has many advantages over conventional pneumatic cylinders such as high force to weight ratio, various installation possibilities, lower compressed–air consumption and low price [9].

Many studies have reported on the developments of McKibben actuator application for instance in a survey paper on McKibben application [7], bio-robotics [10], rehabilitation [2], the modelling study of the McKibben [8,9,10]. In particular, McKibben muscles are considered to be appropriate for applications in wearable robots and musculoskeletal robots because of their compliance and contraction characteristics are similar to those of human muscles [8]. However, most existing McKibben muscles have the disadvantage that their outer diameters are within 10 mm and 40 mm. Moreover, the entire muscle becomes rigid under a pressurised state, which makes it difficult to deform. Therefore, the development of thin McKibben muscles was introduced by Suzumori lab in 2013 [11] to overcome this issue as illustrated in Figure 1. Thin McKibben muscle is a versatile actuator which enable bending even under pressurised state and it is lightweight with a contraction ratio of approximately 25%, which is comparable to human muscles. Moreover, it has a contraction force several times larger than that of human muscles, and this can be further increased by bundling the muscles and employing a multifilament structure [12,13].

Bending performance is vital for deformability and reachability in practical application. There are several studies like using SMA – fishing-line integrated with McKibben actuator for realising the bending motion [14], braiding technique for bending effect [15] and kinematic analysis for the facilitation of the model [16]. Some design of bending performance also inspired by a biological system like mimicking human index finger [1], KITECH-hand focusing on MCP joint finger [17], EthoHand focusing on thumb finger [18] and highly mimicking the human hand [19]. Due to its bending performance, thin McKibben actuator also came with the benefits of dexterous function and power to do daily activities like brushing teeth, wearing clothes, grasping an object and even playing musical instrument. McKibben-style actuators are characterised by its high-level practical analogy with human skeletal muscle and have passive and natural compliance, which follows the character of skeletal muscle. However, the bending performance of a soft actuator is yet in demand to achieve the best result of the desired application.

This paper presents the segmentation of a soft body and its bending performance using thin McKibben muscle actuator inspired by the flexibility of a human finger. This actuator consists of four thin McKibben muscle with 1.30 mm width and 120.0 mm length arranged in parallel, compacted in a soft body and a simple integration of knitted on the actuator as a pulley inspired by finger flexion mechanism. The point of knitting was used to divide a variant of segment

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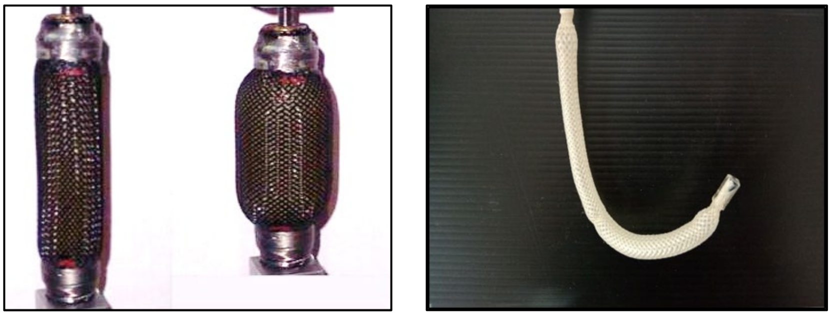
length of the actuator. The bending behaviour was evaluated using an experimental test with a variety of pneumatic input pressure with respect to the segmentation length. This segment length technique was able to produce high bending angle output of 42º compared to the unsegmented length of 40º, increasing 1.0 times to the original value. This finding might promote the benefits of the segmentation effect concerning the bending angle performance of the soft actuator.



(a) (b)

Figure 1: McKibben Actuator when under pressurised state. (a) Conventional McKibben and (b) thin McKibben.

SOFT BODY STRUCTURE ACTUATED USING THIN MCKIBBEN ACTUATOR

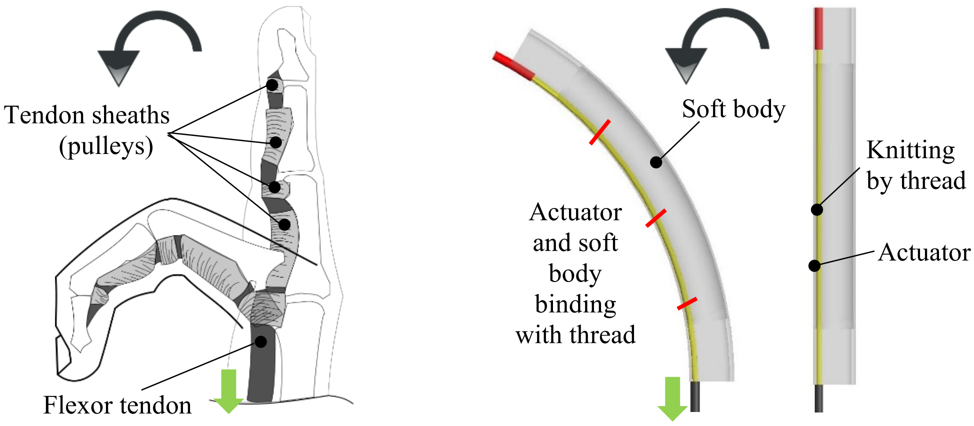
In this section, the design and fabrication of the soft body actuator structure are demonstrated in detail. It was fabricated by a simple integration of a soft body and thin McKibben muscle. The actuator structure was inspired by the human finger mechanism and able to realise the bending motion with improved bending performance.

Bending Soft Body Design

Between the bones and muscles, there are two groups of tendons in a human hand. Those straighten the fingers are known as extensor tendons, and those bending the fingers are known as flexor tendons. In this paper, we structure the design based on the flexor tendon as shown in Figure 3, where the ones bending the fingers. From Figure 2 (a), a series of tendon sheaths are knitted around the tendon, which functions like pulleys to help the fluent motions of bending on flexor tendons. A geometric representation of the soft body actuator structure based on flexor tendon mechanism as shown in Figure 2 (b). A knitted point binding by a thread as a tendon sheath (pulleys), thin McKibben as muscle analogous to the flexor tendon and soft body as the bone.

Figure 3 shows the detail visualisation of the bending actuator. It consists of a casting cylindrical soft body made by silicon rubber, thin McKibben muscles represented by four yellow colour structure arranged in parallel and placed inside the soft body. This muscle was connected to the air compressor through a flexible pipe as in Figure 4. Two end caps as the liner to fit the body and actuator. The arrangement of four actuators would introduce bending motion in four directions, $+x$, $-x$, $+y$ and $-y$.

The methodology of knitting the thin McKibben muscle and soft body also shown, as seen in Figure 3. By using thread, the muscle and body were knitted. This knitting point function as a pulley and characterising it by adding a point of pulleys to observe the bending performance by point character as well as human finger tendon for maximum bending. This knitting point also characterises the actuator length to the segmentation. Bending motion can be obtained by pressurising the actuator pneumatically. By changing the air volume and the number of active actuators, the body was able to exploit the configuration in a workspace and increase the ability on manipulation.



(a) (b)

Figure 2. Working principle of the soft body bending: (a) bending finger under the effect of the pulleys (tendon sheaths) during finger flexion and (b) soft body bending inspired by finger flexion.

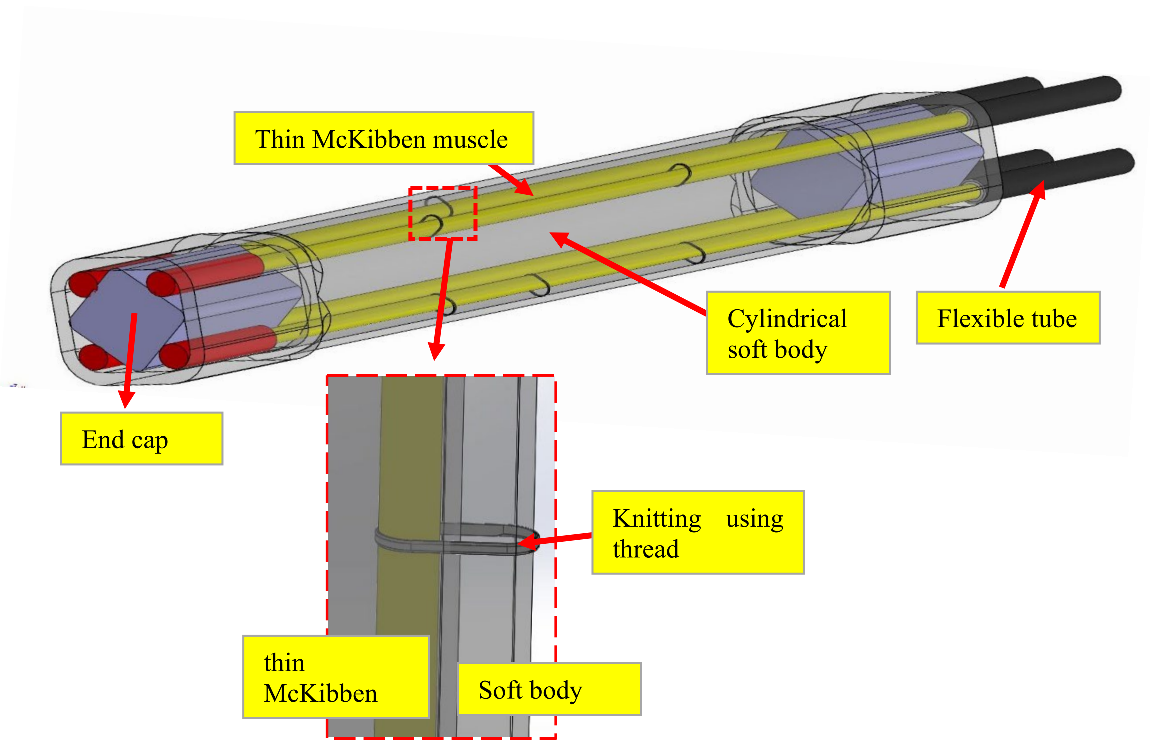


Figure 3. A conceptual design of soft body structure.

A customised schematic diagram is established as in Figure 4. The thin McKibben muscle actuator was pressurised by air compressor through a flexible tube, solenoid valve and FRL unit. An FRL unit was used to filter and measure the internal pressure of the actuator while the actuation was controlled via a microcontroller Arduino UNO. The bending test was conducted when the internal pressure of the muscle increased from 0.1 MPa to 0.4 MPa, with an increment of 0.1 MPa.

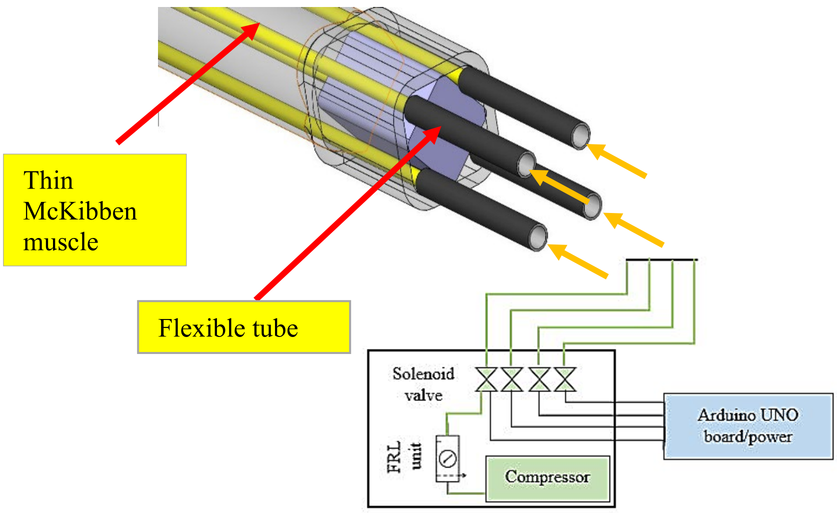


Figure 4. Schematic overview of the actuation setup.

Thin McKibben Muscle Actuator

In this study, thin McKibben muscle was used as illustrated in Figure 5. It is very thin, lightweight, and flexible muscle [20,21] that enables the bending motion. This actuator consists of an inner tube made from silicone rubber and covered by an outer sleeve, which made of knitted fibre of 0.12 mm monofilaments as presented in Figure 5(b). The operation principle is the same as that of conventional McKibben muscles. When compressed air was supplied to the thin McKibben muscle, the inner rubber tube expanded in the radial direction under applied pressure and contracted in the axial direction which led to the pulling force as shown in Figure 5(c) [13,22]. The size of the actuator used in this experiment was 1.8 mm in outer diameter, 1.3 mm outer diameter of a rubber tube with 0.9 mm inner diameter and 120.0 mm in length. The parameters of thin McKibben muscle used for this experiment are listed in Table 1 and the characteristics of this actuator are shown in Figure 6 [22]. Contraction rate here is define as the ratio of the amount of deformation to the initial length while one endpoint of a thin McKibben muscle was fixed. This thin McKibben actuator exhibit a contraction ratio of 20% at 0.3 MPa. The maximum contraction ratio was 25% when the air pressure was at 0.5 MPa. Based on the graph, the contraction became saturated when the pressure starts from at 0.45 MPa. This actuator was controlled via pneumatically.

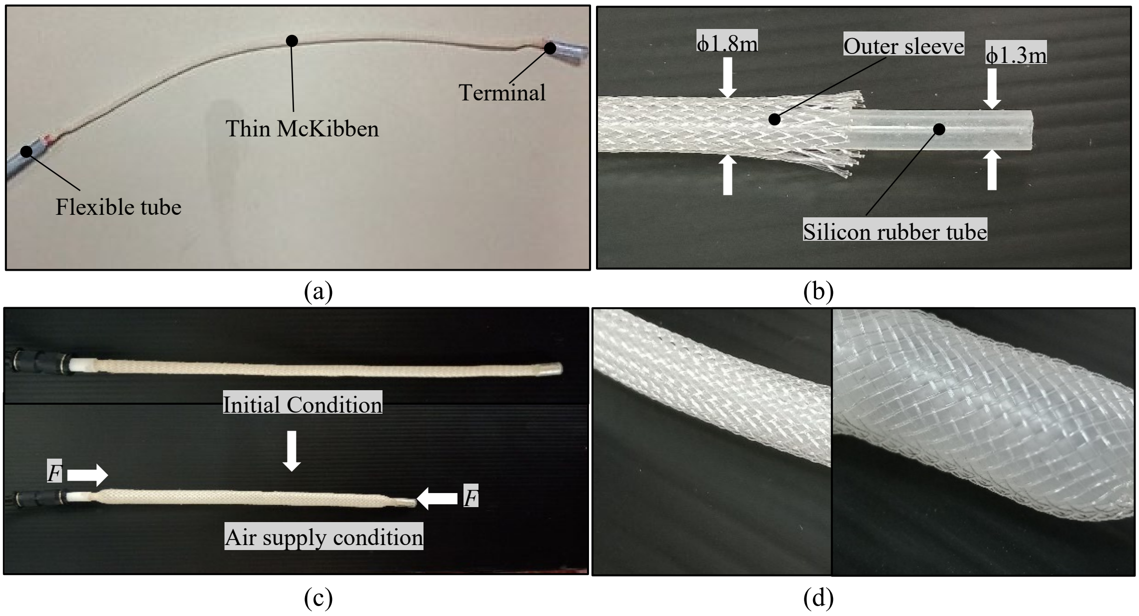


Figure 5. Thin McKibben actuator. (a) overview of McKibben actuator, (b) diagram of thin McKibben muscle, (c) operation principal of actuator, (d) pressurised and unpressurised state.

Table 1. Specification of thin McKibben muscle actuator use in this experiment.

Parameters	Unit	Value
Diameter	mm	1.8
Initial length	mm	120
Outer diameter of the silicone tube	mm	1.3
Hardness of the silicone tube	Shore A	40
Fibre angle	°	18
Number of outer fibres	-	32

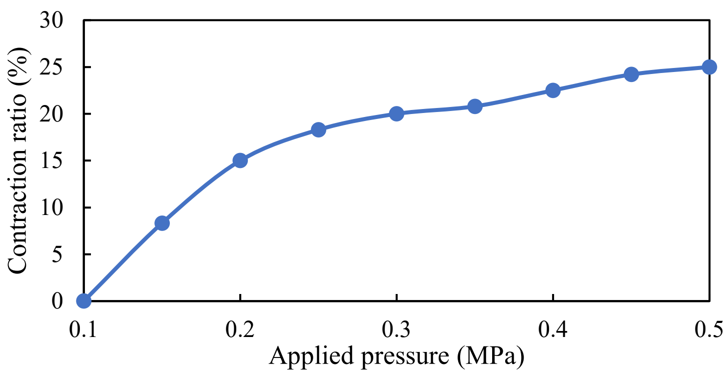


Figure 6. Characteristics of 1.3 mm thin McKibben muscle: the relation between contraction ratio and applied pressure.

The physical prototype of the proposed bending soft body is presented in Figure 7, with an outer diameter of 15 mm, 135 mm length and total weight of 35 g. Silicone rubber (KE-1241: Shin-Etsu Silicones, hardness of 30 durometer) was used for one cylindrical soft body and two end caps while four thin McKibben muscle actuators were placed axially in the body. Four flexible tubes were connected to the muscles and thread was used for knitting. This mechanism was configured with soft materials only. For the body and end cap, the fabrication was using casting method with thin McKibben (in the market), a 4 mm polyethylene tube for flexible tube also (in the market) and the base platform by 3D print with ABS filament material. In every thin McKibben muscle, one end was sealed in order to secure contraction motion when the actuator was pressurised. This prototype bending actuator could easily be changed and detached for other purposes.

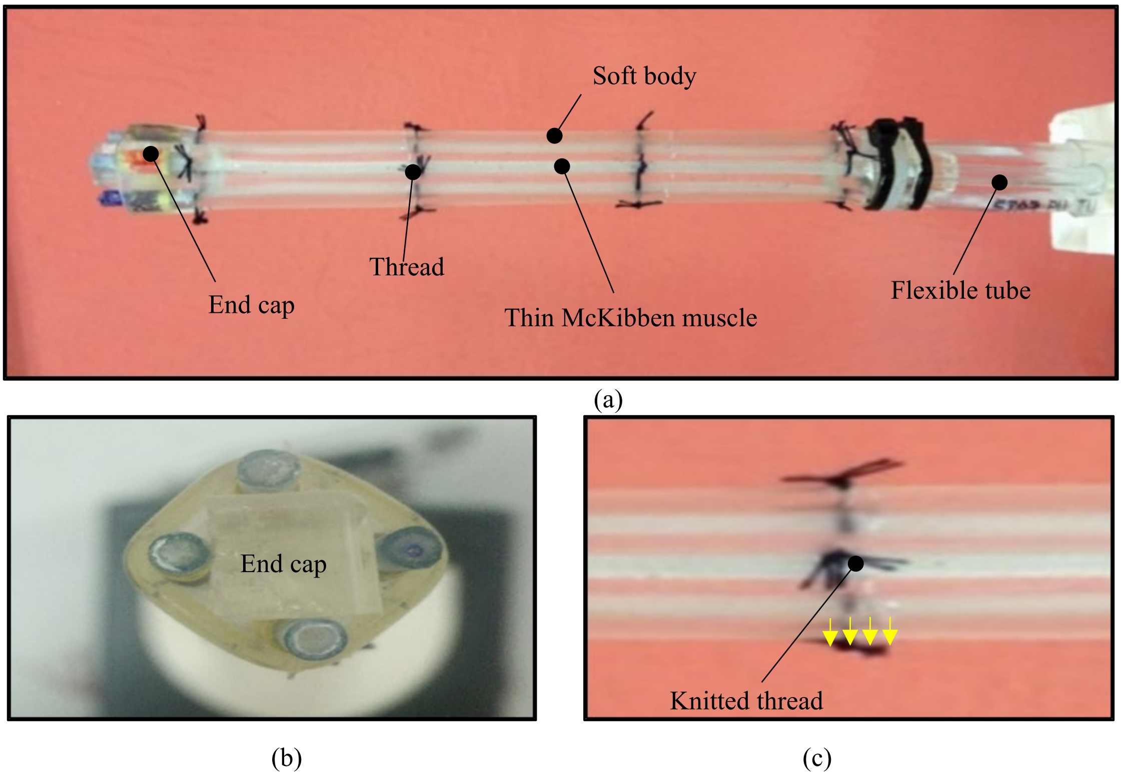


Figure 7. Soft body structure: (a) structure of the soft body, (b) end cap arrangement to fit the thin McKibben and the body and (c) knitted method to tie the McKibben close to the wall of body.

Experimental Setup

Figure 8 shows the experimental system of the bending actuator. The system consists of an air compressor, electro-pneumatic regulator, DC power supply, the soft body actuator, air connectors and valves. The operating principle is as follows: the soft body actuator was pressurised by air compressor through a filter (to filter the air) and an electro-pneumatic regulator was used to regulate the operating pressure from 0.1 MPa to 0.4 MPa, with an increment of 0.1 MPa. As the pressure of the soft body actuator controlled by a solenoid valve and microcontroller, the actuator contracted and expanded in a radial direction and drove the body to bend.

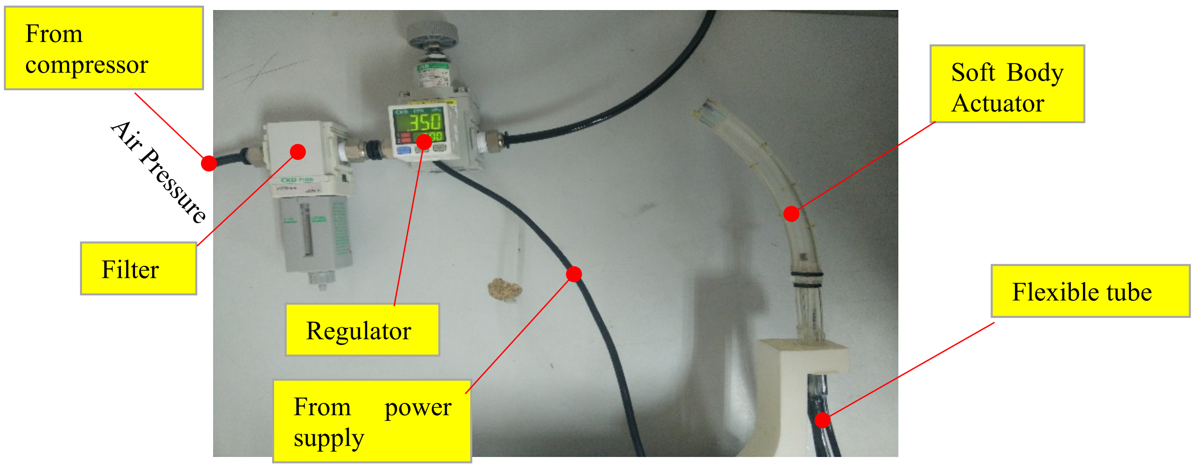
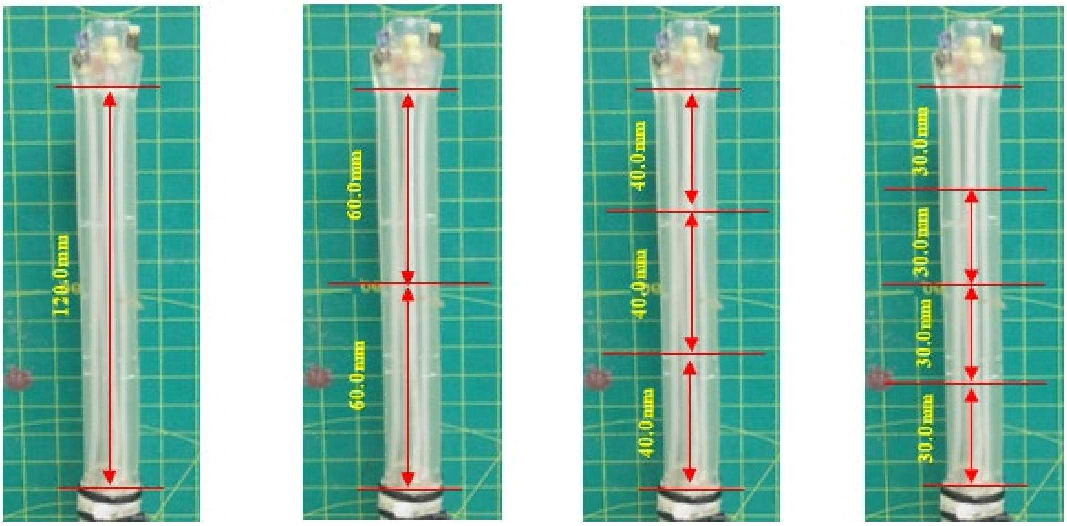


Figure 8. Operation Principal

Figure 9 below shows the model of various segment length set up on the actuator to vary the bending performance. It was setup by knitting the muscle to the desired segmentation length, model A without knitted point (no section length, no segment), model B with one knitted point (section length 60 mm, two segments), model C two knitted points (section length 40 mm, three segments), and model D three knitted points (section length 30 mm, 4 segments), as shown in Figure 9 (a), (b), (c), and (d), respectively.



(a) Model A (b) Model B (c) Model C (d) Model D

Figure 9. Various segment length on the actuator tested for bending performance.

RESULT AND DISCUSSION

Four different pressure tests were conducted, from 0.1 MPa to 0.4 MPa with an increment of 0.1 MPa with respect to variable section length of muscle as can be seen in Figure 10. The experiment was conducted by sequence from 10(a) to 10(d) and the response of a soft body with various pressures are illustrated in Figure 10. Five tests were conducted for each model. The experimental parameters used for this experiment are listed in Table 2.

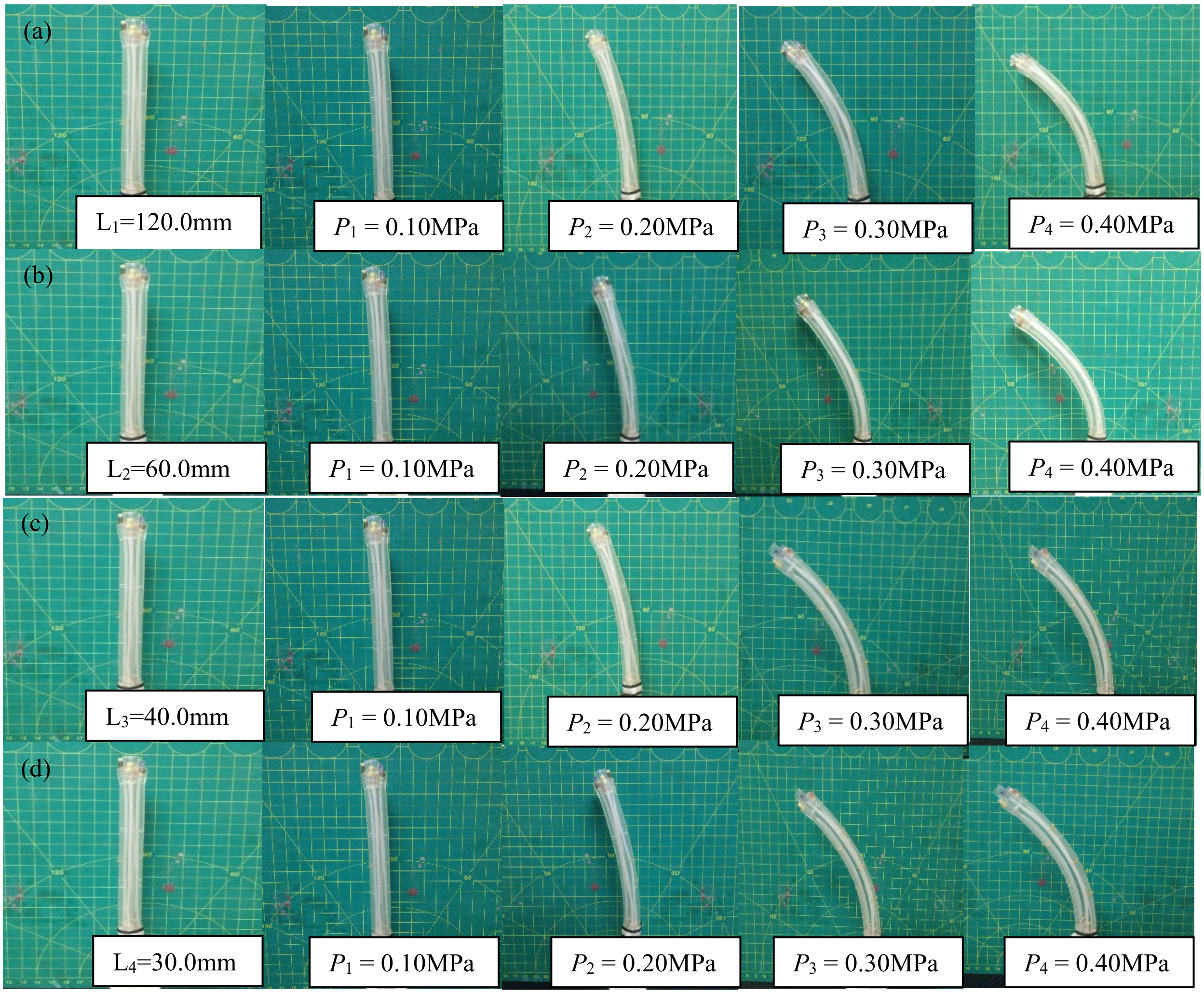


Figure 10. Muscle bent at a certain angle when given different air pressures.

Table 2. Experimental parameters.

Parameters	Unit	Value
Length of McKibben	mm	$L_1 = 120$
Thickness of McKibben	mm	$t = 1.3$
Quantity of McKibben		$q = 4$
Operating Pressure	MPa	$P_1 = 0.10, P_2 = 0.20, P_3 = 0.30, P_4 = 0.40$
Length of the section	mm	$L_2 = 60.00, L_3 = 40.00, L_4 = 30.00$

In this study, the bending angle θ in Eq. (1) is defined as the angle between the vector of the tip of the actuator and the root vector of the actuator as shown in Figure 11, where a coordinate mat was used to measure the bending angles.

$$\text{Bending angle, } \theta = \tan^{-1}(x/y) \tag{1}$$

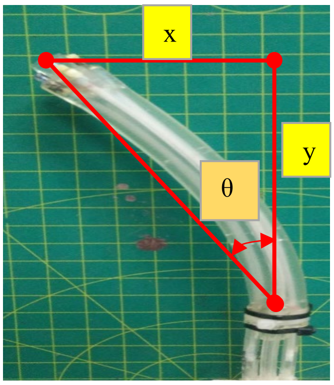


Figure 11. Definition of bending angle of the actuator.

Next, the influence of the segmentation length on the behaviour of bending motions were examined. Figure 12 shows the relationship between applied pressure and the bending angle of three samples of segmentation length; namely model B, model C, and model D, and original actuator muscle without segmentation (model A). It can be seen that the bending angle increased as the number of segment increases. It is evident as shown in Table 3, increasing the segmentation or knitted point increases the bending angles. The bending angle increase from approximately 40° to a maximum of approximately 42°. This showed that the segmentation increased the bending angles by approximately 1.0 times. The bending angle of model D was the largest compared to other section for all applied pressure, follow by model C, and model B. However, the bending angle on model A showed a drastic increment when the air pressure increased resulted in exceeding the bending angle of model B after 0.2 MPa and bending angle of model C approximately after 0.35 MPa. However, the bending angle of model A did not surpass the bending angle of model D at all applied pressure. A similar result was displayed for the model B and model C, where the bending angle showed an increment when the air pressure increased but the angle was smaller compared to model D.

The trend from model B and model C in Figure 12 was slightly different compared to model A and model D. Model B shows that the degree dropped at 0.3 MPa and model C at 0.4 MPa. This indicated that knitted point or segmentation could not be due to the number of knitted point, but instead because of individual differences in the thin McKibben muscles or on account of measurement errors or the knitted itself. We also found that the trends show a decrease in the bending angles when pressure increase as can be seen in Figure 13. This is due to the influence of increasing weight in thin McKibben, which resulted in the interference on the bending of model B and model C that explains the difference. All data were performed using a general linear model in Minitab; the model shows the P-value of < 0.005 with R-squared (adj) is 98.81%, which indicated the data tested is significant and strongly related.

Table 3. The degrees of bending angles for each model.

	Model A (°) [Ref]	Model B (°)	Model C (°)	Model D (°)	Model B (°)	Model C (°)	Model D (°)
0.1 MPa	0.00	0.00	0.00	7.13	→ 0.00	→ 0.00	↑ +7.13
0.2 MPa	16.26	16.26	19.71	21.39	→ 0.00	↑ +3.45	↑ +5.13
0.3 MPa	30.26	24.23	32.35	33.69	↓ -6.03	↑ +2.09	↑ +3.43
0.4 MPa	40.36	33.89	38.01	41.72	↓ -6.47	↓ -2.35	↑ +1.36

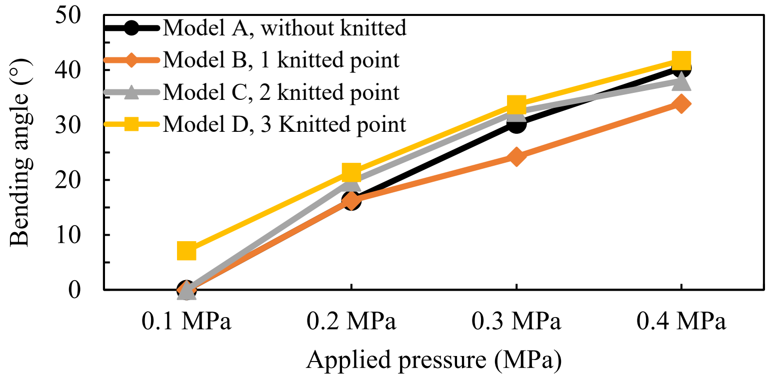


Figure 12. The relationship between the applied pressure and bending angle of the original length and segmentation.

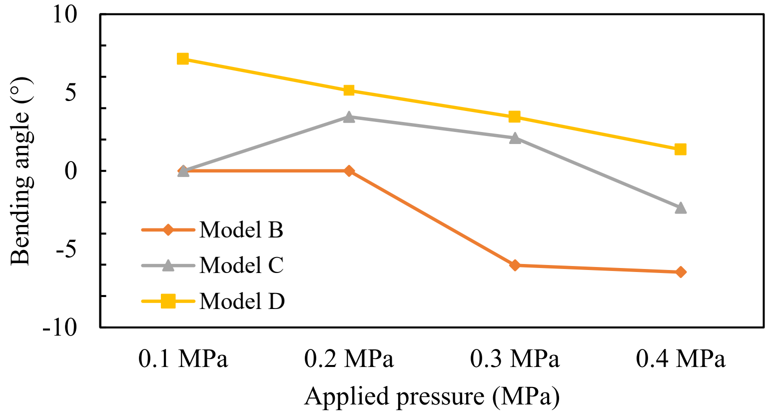


Figure 13. Trends of knitted point for each model.

The graph between segment length and bending angle also showed an apparent relationship, as illustrated in Figure 14. The bending angle of model D was dominant than other models which indicated that more section point produced more bending angle at all input pressure. The bending already started in model D when the air pressure is 0.1 MPa compared to the others have not started bending yet at the same pressure reading. It is believed that the knitted point influenced the bending angle as inspired by finger movement, where the knitted point can be compared to tendon and thin McKibben to muscle.

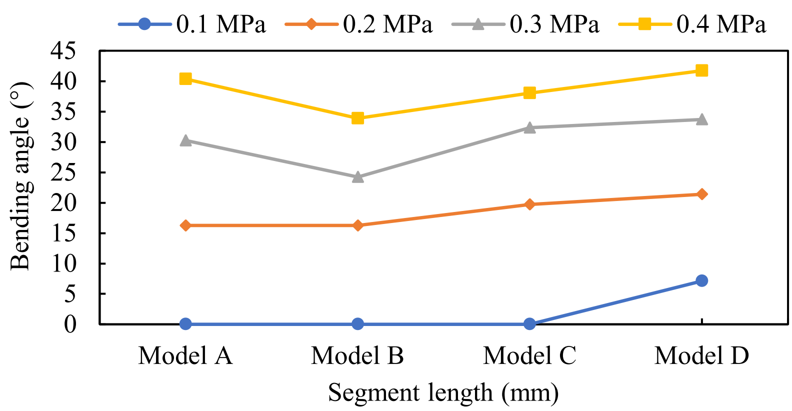


Figure 14. The relationship between the section length and the bending angle of the tested actuator.

CONCLUSION

The key innovation of the design is the use of thin soft McKibben as the actuator due to the excellent performance where it is lightweight, has high power output and significantly compliance and flexible. This feature leads to a new concept that is different from most of the conventional robots, which are highly restricted with predetermined motion. The biological structure always give opportunity for better improvement, where the inspiration from the flexibility finger flexor tendon considerably improved the ability of the bending motions as a result of the knitting or section point from tendon pulleys. We compared the segmentation length proposed with the original length muscles consisting of the same thin muscles in parallel. The proposed knitted point showed a significant improvement in terms of the bending angles

(40% original, and 42% after with 3 point of section length) with the same generating force, increasing approximately 1.0 times from the original value. The experimental result shows that the bending angle increases as the segmentation increases. For future research, an extended experiment on continuum manipulator can be developed to explore the navigation of the soft robot in a dynamic environment such as in search and rescue operation integrated with the knitted point for high manipulation capability.

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