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DEVELOPMENT OF RODLESS TYPE FLEXIBLE PNEUMATAIC CYLINDER AND ITS APPLICATION FOR LONG STROKE MCKIBBEN TYPE ACTUATOR

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ABSTRACT

Recently, virtual reality systems that feed back to human senses have only been realized as visual and acoustic feedback. However, they are not enough to realize the force feedback system for hands, arms, legs and so on. The actuators required for such a system need to be flexible so as not to injure the body. The purpose of our study is to develop a flexible and lightweight actuator which can be safe enough to be attached to the human body. We propose new types of flexible pneumatic actuator that can be used even if the actuator is deformed by external force. In this study, we tested rodless type flexible pneumatic cylinders that have a self holding function for positioning under the condition of no supply pressure. We also developed a new type of McKibben artificial muscle that has a long stroke of more than 80 % of its original length. As a result of our experiment, we can confirm that the tested cylinder is useful to be applied in a positioning system because it consumes less air under the condition of holding. By using the tested Mckibben actuator, we can realize a long stroke lifting motion of a dumbbell whose mass is 6 kg.

KEY WORDS

Rodless Type Flexible Pneumatic Cylinder, Self Holding Function, Long Stroke McKibben Type Actuator, Soft Actuator

INTRODUCTION

Virtual reality has been flourishing as an interactive information technology. Recently, virtual reality systems that feed back to human senses have only been realized as visual and acoustic feedback. However, they are not enough to realize the force feedback system for hands, arms, legs and so on. Furthermore, due to the ageing in Japanese society and the decreasing birthrate, an important problem of providing nursing care for the elderly has occurred. As a result, it is necessary to develop systems to aid in nursing care[1]. The actuators required in such a feedback control system, as for power assisted nursing care of the elderly, need to be flexible so as not to injure the body. The purpose of our study is to develop a flexible and lightweight actuator which can be safe enough to be attached to the human body. We had proposed and tested new types of flexible pneumatic actuators that can be used even if the actuator is deformed by external force[2][3].

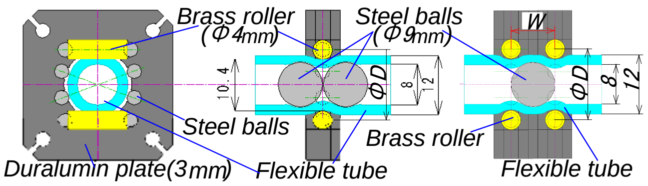
In this study, we investigate the friction in a rodless type flexible pneumatic cylinder proposed in our previous studies[4][5]. We also aim to develop a new type of McKibben artificial muscle that has a long stroke of more than 80 % of its original length.

RODLESS TYPE FLEXIBLE PNEUMATIC CYLINDER

Construction and operating principle

Figure 1 (a) and (b) show the construction of two types of rodless flexible pneumatic cylinders. We call the former, as shown in Fig.1(a), a "Double type" and call the latter a "Single type". The double type cylinder consists of a flexible tube as a cylinder and gasket, two steel balls as a cylinder head and a slide stage that can slide along the outside of the tube. The slide stage has two rollers set on the inner bore of the stage in order to press and deform the tube toward the center of the tube. The construction of the single type cylinder as shown in Fig.1(b) is similar to that of the double type. The single type cylinder uses one steel ball as a cylinder head. The steel ball is held by two pairs of brass rollers from both side of the ball. Compared with the double type, we aim to decrease the friction of the cylinder by decreasing the contact area between the inner ball and inner wall of the tube.

The operating principles of both cylinders are as follows. When the supply pressure is applied to one side of the cylinder, the cylinder head (inner steel balls) are pushed. At the same time, the balls push rollers and move the slide stage while they deform the tubes. In the double type, the two balls of the cylinder head are not connected to each other, that is, each ball can move independently. Therefore, the balls can move along the curved tube in the same manner as a straight tube.

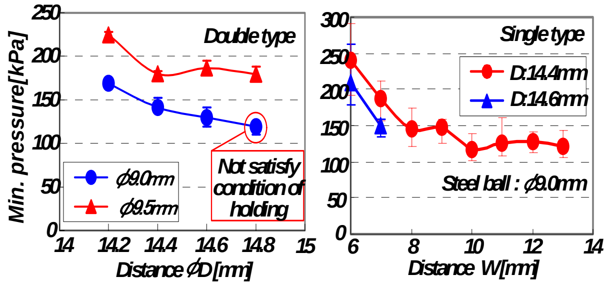


(a)Double type (b)Single type

Fig.1 Construction of rodless type flexible pneumatic cylinder

Minimum driving pressure for actuation

Figure 2 (a) and (b) show results of minimum pressure for actuation of double and single type cylinder using various center distances *D* and *W* (as shown in Fig.1) between the two pairs of rollers as a design parameter. In case of the double type cylinder, as shown in Fig. 2(a), we investigated the relation between the center distance *D* and minimum pressure of the cylinder. In case of the single type cylinder, as shown in Fig.2(b), we investigated the relation between the center distance *W* and minimum pressure using optimal value of distance D of 14.4 or 14.6 mm that can be obtained from Fig.2(a). Vertical lines show the scatter in measured values. From Fig. 2(a), we can see that the cylinder using a distance *D* of 14.6 mm and an inner steel ball with a diameter of 9.0 mm shows the lowest driving pressure of 130 kPa. From Fig. 2(b), it can be seen that the minimum driving pressure of the single type cylinder is gradually approaching the constant value of 120 kPa in the case using the center diameter *W* of more than 10 mm. It can be seen that the lowest driving pressure of the cylinder is 120 kPa. We can reduce about 7.8 % of the friction compared with the double type of cylinder.

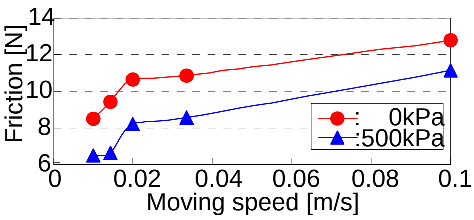


(a) Double type (b) Single type

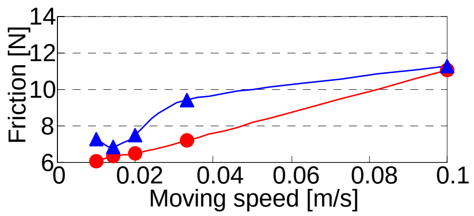
Fig.2 Minimum driving pressure of rodless type flexible pneumatic cylinder

Frictional characteristics

In order to investigate frictional characteristics for actuation of the tested cylinders, we measured the pulling force when we gave a motion to the slide stage of the cylinder at constant speed. Figure 3(a) and (b) show the relation between moving speed of the slide stage and frictional force of the double type and single type cylinder, respectively. In Fig.3, each symbol ▲ and ● shows the experimental results under the condition when supplied pressure of 500 kPa is applied or not to the both side of cylinder chambers. In the case using double type cylinder as shown in Fig.3(a), we can see that the frictional force under the condition of no supply pressure is about 1.4 times as large as the case when supply pressure of 500 kPa is applied to the cylinder. On the other hand, in the case using the single type cylinder, it can be seen that the frictional force when supply pressure is applied to the cylinder becomes larger than the results with no supply pressure. We think that it is caused by following reason: In the case of double type cylinder, the frictional force depends on the contact area between inner steel balls and inner wall of cylinder tube. When supply pressure is applied to the cylinder, the cylinder tube expands and the contact area between the inner balls and the tube decreases. Then it makes the friction decrease. On the other hand, in the case of single type cylinder, the contact area between an inner steel ball and the tube depends on an arrangement of two pairs of brass rollers and the inner steel ball. When the cylinder tube expands with supply pressure of 500 kPa, the contact area between brass rollers and outer bore of the tube increases. So, it makes the friction increase. As a result mentioned above, we can conclude as follows. The double type cylinder has an advantage that it is possible to hold more easily the slide stage at a certain position than in the case using an ordinary pneumatic cylinder on the market, because the tested cylinder has a feature that the frictional force of the cylinder without input pressure is higher than the case when supply pressure is applied. This means that the tested cylinder has a "self holding function" for positioning under the condition of no supply pressure. This is one of important merits of this cylinder.



(a) Double type



(b) Single type

Fig.3 Frictional characteristics of rodless type flexible pneumatic cylinder

MCKIBBEN ACTUATOR WITH ADJUSTABLE STROKE

Construction and operating principle

The tested flexible pneumatic cylinder has some merits such as long stroke pushing and pulling motion, high speed motion of more than 1 m/s and self holding function for positioning. However, the generated force of the cylinder, that is about 15 N with supplied pressure of 500 kPa, is not so enough to apply a force feedback system for human. Therefore, we should consider to increase the generated force of the flexible actuator. A McKibben artificial muscle has been flourishing as a flexible and wearable actuator because of its simple configuration, flexible property and lightweight. Usually, McKibben artificial muscles can generate larger force compared with their weight. However, the actuator can not act a long stroke motion such as more than 25 % of their original length. Then, we aim to develop a new type of flexible actuator by combining the rodless type flexible pneumatic cylinder and McKibben artificial muscles. Figure 4 shows the construction of the tested actuator. It consists of an ordinal McKibben artificial muscle that is made of a silicone rubber tube coated with nylon mesh and a slide stage that can slide along the outside of the tube. The slide stage has two rollers with outer diameter of 8 mm set on the inner bore of the stage in order to press the tube toward the center of the tube. A chamber of McKibben artificial muscle is divided into two chambers by using the slide stage. The rollers in the stage and rubber tube keep the seal even if supply pressure is applied to both chambers. Figure 5 shows the operating process of the tested actuator. The operating principle of the actuator is as follows. The slide stage is fixed. When a free end of the actuator (we call it "A side" for short) as shown in Fig.5②is pressurized, the actuator generates smaller pulling force than the case using a usual McKibben actuator. Then, the tube length of the opposite side (we call it "B side" for short) of the actuator becomes shorter by pulling force. In this condition, we add to pressurize "B side" of the actuator as shown in Fig.5③. "B side" of the actuator works as same as a usual McKibben actuator. Therefore, it can generate larger force than the case when we pressurize only to "A side" of the actuator. After exhausting the air in the B side of chamber, this causes the loosing between the slide stage and the B side of tube end.

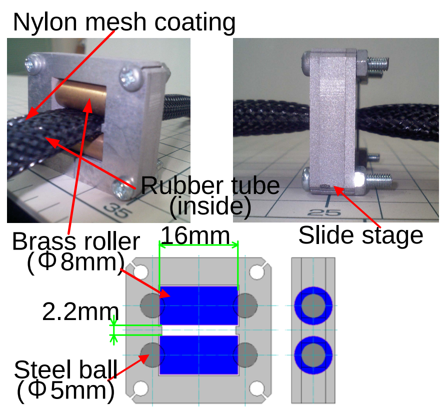


Fig.4 Construction of the Mckibben actuator with adjustable stroke

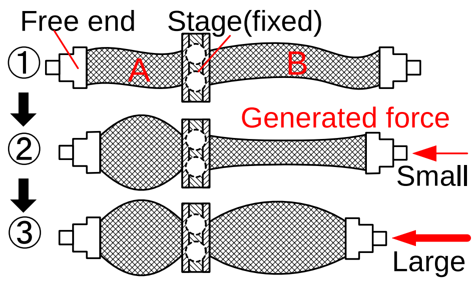


Fig.5 Operating principle of tested Mckibben actuator

By repeating these operations (①→②→③→②→③…) , we can adjust the stroke of the tested actuator statically. It means that the tested McKibben actuator can work a long stroke pulling motion under the condition when there is sliding friction between an object connected with the actuator and the table.

Generated force of tested actuator

Figure 6 shows the relation between supplied pressure in "A" or "B" side of chamber and generated force of the tested actuator. In the experiment, we use the tested actuator with a whole length of 500 mm without connectors and changed the ratio of lengths between "A" and "B" side of tubes every 100 mm. The results as shown in Fig.6 include two types of experimental results. One is the generated force when we only pressurized "A side" of the actuator. The other is the case when we added to apply supply pressure to "B side" of the actuator under condition when "A side" is pressurized at 400 kPa. In Fig.6, each symbol shows the results using various combinations of lengths of "A" and "B" side of the actuator. Each input pressure into "B side" of chamber for each experimental condition is given until a leakage occurs between "A" and "B" side chamber. From the left side in Fig.6, we can see that each relation between input pressure and generated force when we apply the pressure to "A side" is almost same even if the length of "A side" of the actuator is changed. Maximum generated force in this case is about 21 N. From the right side in Fig.6, it can be seen that the generated force becomes larger than the case when "A side" of chamber is pressurized only. The maximum generated force in this case is about 5 times as large as the previous case; that is about 110 N. This value is almost the same as the case using a usual McKibben actuator. We can see that the generated force increases according to length of "B side" of the actuator even if we give a same input pressure. It means that the tested actuator has same characteristics of a usual McKibben actuator that can generate larger force according to the tube length of the actuator. In the experiment, we found a leakage between two chambers of the actuator when supply pressure becomes larger. The leakage is generated as follows. When supply pressure in two chambers becomes larger, the rubber tube expands. Then the thickness of the tube becomes smaller. It generates the leakage between two chambers at the point of slide stage. Therefore, the maximum generated force depends on the sealing characteristics of the actuator. We think that it is possible to increase the generated force of the actuator by improving the construction of the slide stage and rubber tube so as to keep the seal for higher input pressure.

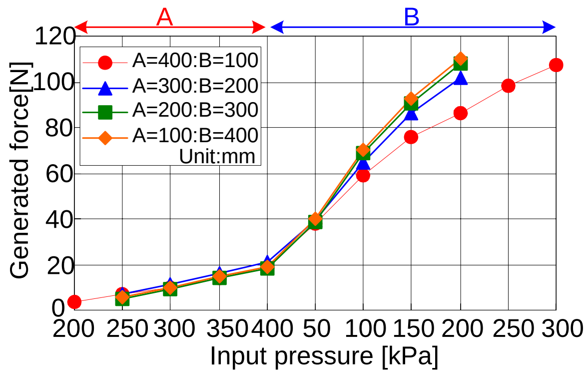


Fig.6 Experimental results of tested McKibben actuator

LONG STROKE MCKIBBEN TYPE ACTUATOR

Construction and operating principle

The tested McKibben actuator mentioned above can act a long stroke motion by changing the length of the tube connected with the load statically. However, the tested actuator could not realize a long stroke motion under the condition of constant load. Therefore, we proposed and tested a new type of McKibben actuator that can work continuously in a long stroke motion. Figure 7 shows a construction of a long stroke McKibben type actuator and experimental equipment for measuring the generated force of the actuator. The actuator consists

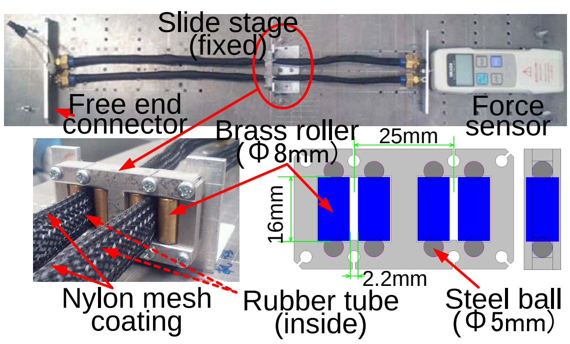


Fig.7 Construction of long stroke McKibben type actuator and its experimental equipment

of two McKibben actuators with adjustable stroke that both actuators are arranged parallel with distance of 25 mm. Each end of two actuators is connected with an aluminum plate. One end of the actuator can move freely; that is a free end. The other is connected with a load or a digital force sensor (IMADA Co.Ltd. DSP-100). The slide stage and the force sensor are fixed on the table.

The operating process of the long stroke motion using tested actuator is shown in Fig.8. We call the upper side chambers of stage "A side". Each a left and right chamber located under the stage is called "B side" and "C side", respectively. The operating principle of the actuator is as follows. One end of the actuator ("B side" and "C side") connected with a load that was set toward the ground. The other ("A side") located on upper side of the fixed stage. First, we apply constant supply pressure to "A side" of chambers. At the point of the fixed stage, the "A side" of tubes generate a small pulling force toward the upper side as shown in Fig.8②. By expanding of "A side" of tubes, the tubes are hard to pull down toward "B and C" side even if a larger downward pulling force is applied to the tubes. It is caused that "A side" of tubes function as a stopper at the point of narrow clearance between two rollers. In the condition, when we pressurize "C side" of chamber, "C side" of tube works as a McKibben artificial muscle and generates larger upward force. Then the distance between the stage and the lower side end connecter becomes a little shorter, an axial deflection in "B side" of tube is produced as shown in Fig.8③. At the same time, "B side" of tube is pulled into the slide stage by pulling force generated in "A side" of tubes and stretched tightly between the stage and connecter. In the same manner as the previous one, when the pressurized chamber is changed from "C side" to "B side", the distance between the stage and the end connector becomes shorter while the actuator holds a lifting force of the load as shown in Fig.8④. By repeating these operations (②→③→④→③→④···) , the actuator can realize a continuous lifting motion with a long stroke of more than 80 % of its original length even if it is under the condition of the constant load such as a gravity. And we can control the position of the load by adjusting the number of repetitions of these operations (③→④→③→④···).

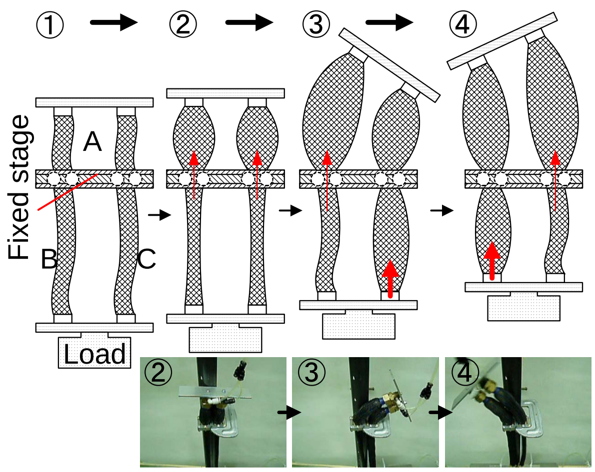


Fig.8 Operating principle of long stroke McKibben type actuator

Experimental results of long stroke lifting motion

Figure 9 shows the view of a long stroke lifting motion using the tested actuator. In Fig.9, each figure shows the state of the actuator with time. The number of left end in each figure shows the time from the beginning of the moving. In the experiment, the actuator is set in the vertical position and the slide stage is fixed on a pole. The lower end of the actuator is connected with a stainless dumbbell whose mass is 6 kg. The length of the actuator without inlets and connectors is about 500 mm. The operation of the actuator is done as follows. First, "A side" of chamber is pressurized with supply pressure of 400 kPa as shown in Fig.9①. Then, we give supply pressure of 400 kPa to "B and C side" of tube alternately every 1 second through two on/off control valves (Koganei Co.Ltd. G010HE). It can be seen that the tested actuator can realize the long stroke lifting motion of about 400 mm for 9.4 seconds while the free end connector moves as an oscillating motion. From Fig.9③and ⑤, we can confirm that it is hard to pull down the tubes under condition of pressurized in upper chambers even if the axial deflection in a lower side of tube is produced. By exchanging the pressurized chambers and the procedure of operation in the actuator, the actuator can move toward opposite direction, because the moving direction of the actuator depends on its operation, it does not depend on the direction of the load.

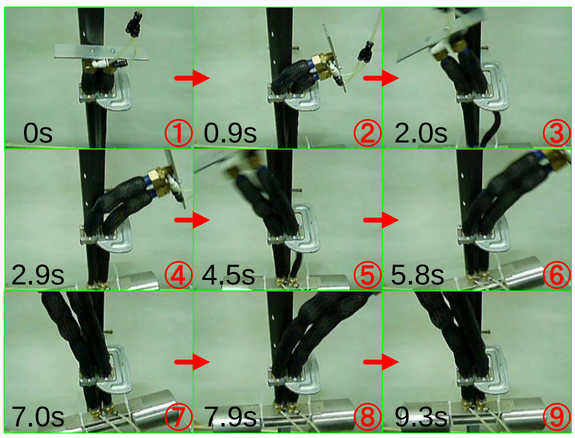


Fig.9 View of a long stroke lifting motion using tested actuator

Generated force of tested actuator

In the same manner of the McKibben actuator with adjustable stroke, we investigate the relation between the input pressure and the generated force of the long stroke McKibben type actuator. Figure 10 shows the relation between supply pressure in "A side" or "B" and "C" side of chamber and generated force of the tested actuator. The experimental conditions for measuring the generated force are almost the same as the case using the McKibben actuator with adjustable stroke. As a point of difference from the previous experiments, we gave the same supply pressure to both "B" and "C" side of chambers in measurement. In Fig.10, each symbol shows the results using various combinations of lengths of "A", "B" and "C" side parts of the actuator. From Fig.10, we can see that the relation between the input pressure and generated force of the actuator is similar to previous results as shown in Fig.6 such as an increasing tendency of generated force when we apply the pressure to both side (A, B and C side) of chambers. It can be seen that the maximum generated force using the tested actuator is about 2 times as large as previous one, that is about 220 N, because two adjustable actuators were used in the actuator. As a result, we can confirm that the maximum generated force of the actuator depends on the sealing characteristics, because the generated force of a McKibben actuator becomes larger according to supply pressure. Therefore, it is possible to develop the actuator that can generate higher force by changing the configuration of the slide stage and material of the rubber tube and coating.

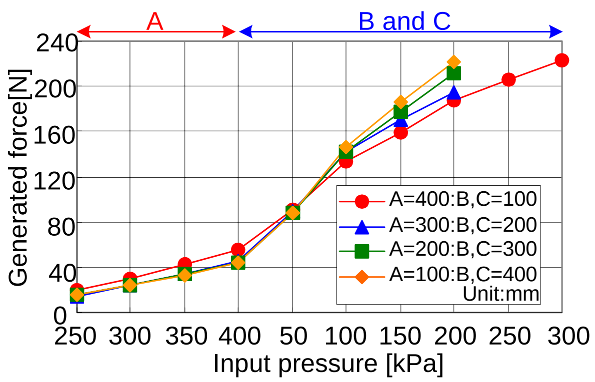


Fig.10 Experimental results of long stroke McKibben type actuator

CONCLUSIONS

This study aiming at the development a new type of McKibben artificial muscle and investigation about the friction characteristics of the single and double type rodless flexible pneumatic cylinder can be summarized as follows:

1) As a result using the single type cylinder, we found that the frictional force increases according to input pressure. We conclude that it is caused that the contact area between rollers and the tube increases according to expansion of tube for supply pressure.
2) In case of double type cylinder, we found that the frictional force with no input is about 1.4 times as large as the case when supply pressure of 500 kPa is applied because of decreasing the contact area between the inner steel balls and tube according to input pressure. As a result, we can confirm that the tested cylinder has a self holding function for positioning under the condition of no supply pressure.
3) We proposed and tested the McKibben actuator with adjustable stroke that is combinied the rodless type flexible pneumatic cylinder and a usual McKibben artificial muscle. As a result of experiment, we found that the maximum generated force is about 110 N, and this limit depends on the sealing characteristics of the actuator.
4) We proposed and tested the long stroke McKibben type actuator that has a parallel arrangement of two McKibben actuators with adjustable stroke. As a result, the tested actuator can realize a long stroke lifting motion, such as more than 80 % of its original length, of a dumbbell whose mass is 6 kg.

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