Development of Flexible Robot Arm with Backdrivability Using Flexible Linear Stepping Actuators

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***Abstract*—Development of soft actuators for the power assisting devices and rehabilitation devices has been required based on aging society in Japan. However, a flexible actuator that can generate both larger force and longer displacement has not been developed. It is also difficult to realize a flexible displacement sensor with long stroke while deforming its form according to the actuator's shape. In the previous study, the flexible actuator with larger force and longer stroke that can adjust its stroke by giving a stepping motion using pneumatic balloons and brakes was proposed and tested. However, the speed of the actuator is too slow to apply to rehabilitation motion. In this paper, the improved stepping actuator using pneumatic cylinders with two types of strokes instead of pneumatic balloons is described. The position control of the improved actuator is carried out. A flexible robot arm that can expand and contract using three improved stepping actuator is also proposed and tested. As a result, it can be confirmed that the attitude of the robot arm can be easily controlled by giving stepping motion of each actuator.**

***Index Terms*—flexible robot arm, flexible linear stepping actuator, attitude control using stepping motion**

I. Introduction

Under the situation of aging society and decreasing birth rate in Japan [1], development of soft actuator for the rehabilitation and power assisting devices [2]-[5] has been required. A rubber artificial muscle is well-known as a wearable actuator. Because it generates larger force even if its mass is small. However, the muscle cannot work with longer stroke. The maximum displacement of the muscle is less than one fourth of its original length [6]. In addition, the generated force of the muscle decreases according to the increase of the displacement of the muscle. As a long stroke flexible actuator, a flexible pneumatic cylinder was proposed and tested [7]. As applications of the developed cylinder, a flexible robot arm for wrist rehabilitation using three flexible pneumatic cylinders was proposed and tested [8], [9]. From these applications, the validity of flexible pneumatic cylinder for rehabilitation devices was confirmed. However, the generated force of the cylinder that depends on its sectional area is not so large. Therefore, in order to develop a power assisted device for nursing care and a rehabilitation device that can give larger motion for patient with stronger force, it is strongly required to develop a flexible actuator that can generate both larger force and longer stroke. It is also difficult to develop a flexible displacement sensor with long stroke while deforming its form along to the shape of flexible actuator. In ideal, the flexible actuator with larger force and longer stroke that can adjust its stroke without sensor is desired. To satisfy such a greedy demand, in the previous study, the flexible linear stepping actuator was proposed and tested [10]. It consists of two pneumatic balloons and brakes. However, the moving speed of the tested actuator is very slow. In this paper, the improvement of the linear stepping actuator for speed-up is described. In order to develop rehabilitation device that can move upper limb with larger area, flexible robot arm with backdrivability using three linear stepping actuators to realize larger rehabilitation motion is proposed and tested. The control system using an embedded controller and the performance of the control system is also described.

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II. Previous Flexible Linear Stepping Actuator

As a flexible pneumatic actuator that can generate larger force and work with a longer stroke, the flexible linear stepping actuator as shown in Fig. 1 was proposed and tested [11]. The tested actuator can also adjust the displacement without sensors by giving the stepping motion. The actuator consists of two doughnut-shaped balloons such as a diaphragm, two pneumatic driven brakes set on left side of actuator, a moving round stage with a pneumatic driven brake and a flexible tube as a rod. The moving stage with a brake located on the center of the actuator is sandwiched by two balloons. The doughnut-shaped balloon that consists of a silicone rubber film with thickness of 0.5 mm has the outer diameter of 48 mm and the inner diameter of 26 mm. The theoretical generated force calculated from the sectional area of the balloon is about 639 N when the supply pressure of 500 kPa is applied. It has the length of 102 mm and the outer diameter of 60 mm. The mass of the actuator without flexible tube (rod) is about 360 g. Fig. 2 shows a schematic diagram of the pneumatic brake using balloon and mechanical chuck [11]. The brake consists of doughnut-shaped balloons with the inner diameter of 24

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mm and the outer diameter of 36 mm, a ring-shaped plastic plate and a mechanical chuck. The mechanical chuck is made of 8 plastic claws set on the stage with the inclined angle of 45 deg. In the tested chuck, two types of claws were used. One is the claw with width of 6 mm. The other is the claw with width of 3 mm. These two types of claws were used, because the generated braking force was larger than that using the same size of claws based on the preliminary experimental result. In addition, the number of claw was also investigated such as 4, 8 and 16 claws. In the previous study, the inclined angle of 45 deg. was calculated as an optimal value theoretically. The generated force of the balloon calculated from the supply pressure of 500 kPa is 280 N and the holding force of the brake is half, that is 140 N.

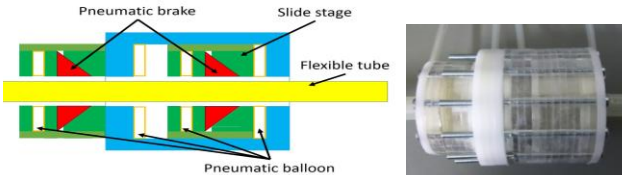

Figure 1. Construction and view of tested flexible stepping actuator.

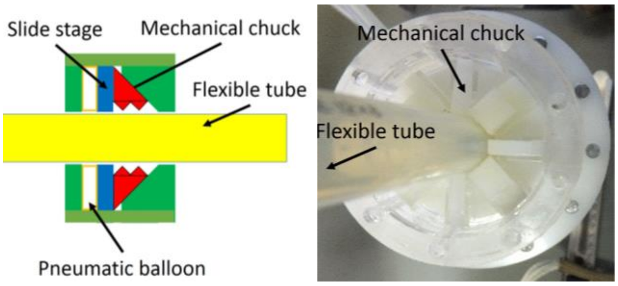

Figure 2. Construction of pneumatic brake using balloon and mechanical chucks.

The operating principle of the tested actuator is shown in Fig. 3. The operating principle is as follows: First, as shown in Fig. 3 (1), the both side brakes are driven for 0.2 s in order to hold the tube. In the condition, the left side balloon is driven for 0.15 s and the moving stage moves toward right as shown in Fig. 3 (2). When the moving stage reaches at the right side wall by giving the input pressure for 0.15 s, the brake on the stage is activated to hold the tube as shown in Fig. 3 (3). After that, while the left side balloon and left side brake are released, the right side balloon is driven for 0.15 s. So the brake on the moving stage keeps holding the tube, the flexible tube is pushed toward left as shown in Fig. 3 (4). By repeating this procedure, the tube can move toward left every a certain stroke. The stroke is same as the width of the balloon chamber of 5 mm.

In the previous study [11], it can be confirmed that the actuator can lift up the load of 30 N with average speed of 5 mm/s. From the experimental result of the generated force, it can be also found that the maximum generated force of 90 N can be obtained. The generated force depends on the holding force of the pneumatic brake. In the actuator, the generated force of the balloon that is more than 400 N is too larger than the braking force. It is possible to decrease the sectional area of actuator according to braking force. In addition, the speed of the tested actuator is slow. The speed is useful to apply rehabilitation devices that do not require a quick motion. However, such a quick motion is required to apply it into a robot and a supporting device. It is necessary to improve so as to drive the actuator faster.

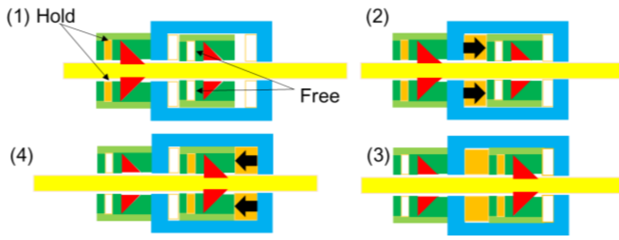

Figure 3. Operating principle of tested flexible stepping actuator.

III. Improved Flexible Linear Stepping Actuator

In order to improve the speed of the actuator, an improved flexible linear stepping actuator is proposed and tested. As a method of speed up, we use pneumatic cylinders in the actuator instead of pneumatic balloons. Fig.4 shows the construction of the improved actuator. Compared with the previous actuator, typical pneumatic cylinders are used instead of the pneumatic balloons. The actuator consists of six double acting type pneumatic cylinders (three of them have the stroke of 50 mm (Koganei Co. Ltd., PBDA 16x50-M) and the others have the stroke of 5 mm (Koganei Co. Ltd., PBDA 16x5-M)) and three pneumatic brakes mentioned above. Two types of cylinders with different strokes were used to realize different stepping movement. The inner cylinder diameter of 16 mm is decided so that the generated force of three cylinders can be larger than the maximum holding force of the brake that is 90 N when the supplied pressure of 500 kPa is applied. Ends of six cylinders are connected with a base stage with a pneumatic brake, they are set every 60 degrees with radius of 33 mm from the center of the base stage. The rod ends of each three cylinders are also connected with the moving stage with a pneumatic brake. By using two moving stage with different strokes, the actuator can move faster every 50 mm for longer displacement. The actuator can also realize the positioning resolution of 5 mm by using shorter stroke cylinders. The actuator also has a backdriability that a flexible rod can be driven by hand when supply pressure is not applied to a pneumatic brake. The improved actuator without a flexible tube has a length of 133 mm and an outer diameter of 80 mm. The mass of the actuator is twice heavier than the mass of the previous one, that is 0.7 kg.

The operating principle is almost same as the previous actuator. Compared with the previous one, the improved actuator can use two types of stepping strokes. Fig. 5 shows the schematic diagram of the control system of the actuator. The control system consists of the improved actuator, seven on/off control valves (Koganei Co. Ltd., G010HE-1), transistors and an embedded controller (Renesas Co. Ltd., SH7125) with a serial communication unit (FTDI Co. Ltd., FT234X). The control procedure is as follows. First, the desired displacement is given through the serial communication unit as serial data. The embedded controller can calculate the repeating times for stroke of 50 mm and 5 mm. For example about the desired position of 275 mm, the controller drives five time cycles of 50 mm stroke movement. The operation for this movement is as same as case using the previous actuator mentioned above. After these motions, the cycle of 5 mm stroke movement is repeated for five times. By using this method, the actuator can move faster when the desired displacement is more than 50 mm and it also moves slower when the desired position is within 50 mm.

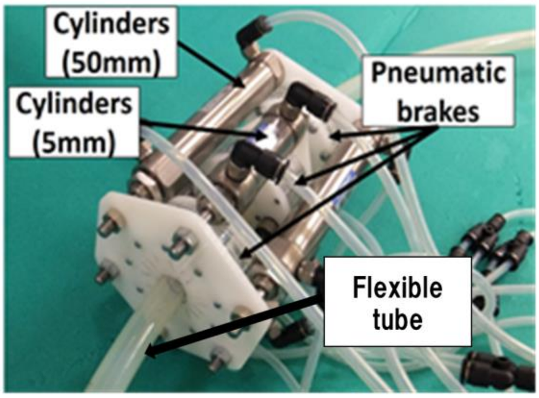

Figure 4. Construction of tested flexible stepping actuator.

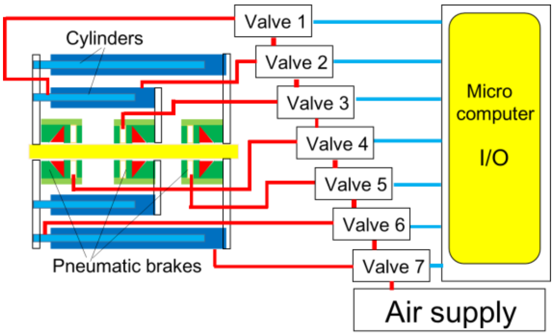

Figure 5. Schematic diagram of the control system of the improved flexible linear stepping actuator.

Fig. 6 shows the transient view of the lifting motion of the load using the actuator. Fig. 7 shows the transient response of the displacement of the actuator when the desired position is changed every 5 or 10 s. In the experiment, the end of the flexible tube connected with the load of 5 N. In Fig. 7, the red and blue lines show the desired and controlled displacement, respectively. From these figures, it can be seen that the actuator can realize the stepping motion for desired position change. It can be also found that the slip is occurred in each step. In particular, it seems that the down movement of the actuator is much affected by gravity of the load mass. However, we can see that the actuator can move with the error within 10 mm for longer motion of 240 mm. It can be confirmed that the actuator is useful to apply to rehabilitation devices that require larger moving distance. This positioning error will be able to be improved by selecting suitable material as a mechanical chuck in the pneumatic brake.

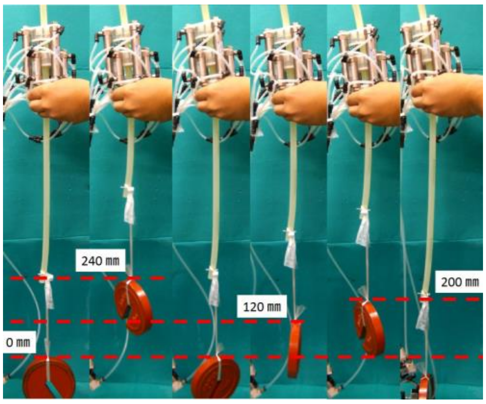

Figure 6. Transient view of lifting motion using tested actuator.

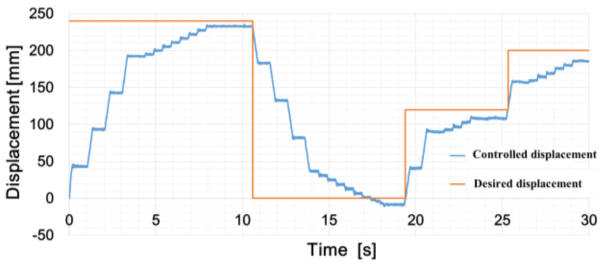

Figure 7. Transient response of the displacement of the actuator

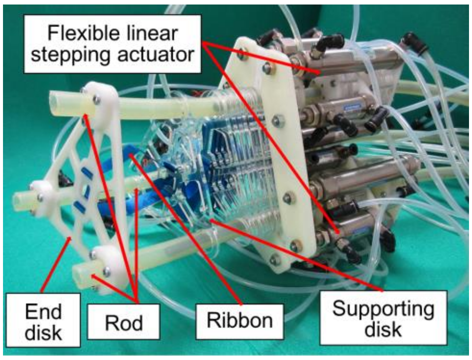

Figure 8. Construction of flexible robot arm using tested actuators..

IV. Flexible Robot Arm with Backdriability

Fig. 8 shows the construction of a flexible robot arm with backdrivability using the improved linear stepping actuators. The robot arm consists of three improved flexible linear stepping actuators, three base connectors, a triangle-shaped end disk and nine triangle-shaped supporting disks. Three improved actuators are set in parallel on the circumference of a circle with every 120 degrees from the center of the robot using three base connecters. The ends of the flexible rods of actuators are connected with the triangle-shaped end disk with same arrangement of actuators. Between the end disk and three actuators, there are nine supporting disks. Between two supporting disks, a ring-shaped nylon ribbon with a width of 12 mm is set on the center to keep the maximum center distance of 50 mm. The tested robot can realize not only expanding and contracting, but also bending toward every

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radial direction. The robot arm can have backdrivability when no supply pressure is applied to pneumatic brakes.

Fig. 9 shows the transient view of the movement of the tested robot in sequential control. The sequential data is produced so that the robot arm can extend and bend toward various directions. The expanding motion of the robot can be realized by giving pushing motion for all actuators at the same time. The bending motion can be done by giving pushing motion for a certain actuator while the other actuators hold their rods by driving pneumatic brakes. From Fig. 9, it can be seen that the robot arm can extend and bend toward various directions. In extending motion, the supporting disks are pushed one by one according to extending rods. In addition, the robot arm can bend larger by using pushing motion. As a result, it can be concluded that the tested robot arm is useful to apply a rehabilitation device with wider moving area for upper limbs while a penitent holds the end stage.

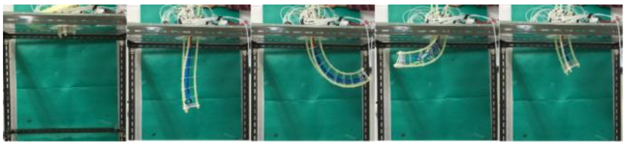

Figure 9. Transient view of various movements of the tested robot arm.

V. Conclusions

In order to realize long stroke, higher moving speed and generated force, the flexible linear stepping actuator using typical pneumatic cylinders was proposed and tested. The position control system using an embedded controller and seven on/off valves was also proposed. The position control using sequential data based on certain stepping motion was carried out. As a result, it can be confirmed that the actuator can control position without any feedback control of displacement. In addition, the flexible robot arm using three tested linear stepping actuators was proposed and tested. The driving test using the robot arm was also carried out. As a result, we can confirm that the tested robot arm is useful to apply rehabilitation devices because of its wider moving area and backdrivability.

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