Development of Tetrahedral Type Rehabilitation Device Using Flexible Pneumatic Actuators

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***Abstract*—Rehabilitation devices help to recover physical ability of patients. This study aims to develop a home rehabilitation device which can be safe to use while patients are holding it by hands. In the previous study, as a portable rehabilitation device, the flexible spherical actuator that was able to give motions to patients while handling it was developed. The device can give rehabilitation motion for upper limb by only changing the relative position of patient's hands. However, the tested device cannot give absolute position for hands for rehabilitation of shoulders. In this study, we aim to develop a low-cost and simple home rehabilitation device for shoulder that can change absolute position of the device. In this paper, to realize position change of the flexible spherical actuator, the development of a tetrahedral type rehabilitation device using extension type flexible pneumatic actuators is described. The construction and the operating principle of the tested device is also described. The attitude control using the tested device and an embedded controller is also carried out. As a result, it can be confirmed that the absolute position of the object can trace the desired coordinate relatively well.**

***Index Terms*— tetrahedral type rehabilitation device, extension type flexible pneumatic actuator, low-cost home rehabilitation device, embedded controller, quasi-servo valve, wire type linear potentiometer.**

I. Introduction

Recently, systems to aid in nursing care [1] and to support activities of daily life for the elderly and the disabled are required in an aging society [2], [3]. Rehabilitation devices help to recover physical ability of patients for keeping "Quality of Life". The actuators used in such a system need to be flexible so as not to injure the human body [4].

This study aims to develop a home rehabilitation device which can be safe to use while patients are holding it by human hands. In particular, from a view point that patients can use it at home by themselves, the device must be able to be used without special knowledge and be easily available at a low cost. From a view point of safety, it is more desired that patients can easily release the device whenever they feel fear and danger.

In our previous study, to realize a home rehabilitation device, a flexible pneumatic cylinder that was able to be used even if the cylinder was deformed by external forces was proposed and tested [5]. A spherical actuator using two flexible pneumatic cylinders which was able to be used on a table as a rehabilitation device for human wrist and arm was also developed [6], [7], [8]. An attitude control of portable rehabilitation device using the flexible spherical actuator was carried out. It was confirmed that the tested device gave rehabilitation motion for patients while they were holding it by both hands. However, the device only gave the relative position between both handling stages. In the next step, it is necessary that can give absolute position change of the handling stage for shoulder rehabilitation and develop a low-cost portable rehabilitation device.

In this paper, a tetrahedral type rehabilitation device using extension type flexible pneumatic actuators that can give the change of absolute position compared to the spherical actuator is proposed and tested. Compared with the device using ordinal rigid actuators, the proposed device has advantage that the devise is safe to use as a rehabilitation device because of small mass and flexibility of extension type actuators. The position control system using the proposed device with low-cost embedded controller and wire type linear potentiometers [9] is also developed. In addition, the position control using the tested devices is carried out.

In Chapter II, the portable rehabilitation device using two flexible pneumatic cylinders is described as an example of previous rehabilitation device. The constructions and operating principles of the flexible pneumatic cylinder and the spherical actuator are described. In Chapter Ⅲ, the problems of the previous device are explained. And the new type of rehabilitation device with a tetrahedral structure is proposed. The constructions and operating principles of a novel flexible extension type actuator and the rehabilitation device using the actuator are explained in detail. In Chapter Ⅳ, an analytical model of the tetrahedral structure type for the position control is proposed and the control system using an embedded micro-computer is described. The

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position control results of the device are shown in Chapter V and it is confirmed that the position control can be realized. Finally, the conclusions of our study are summarized in Chapter VI.

II. Portable Rehabilitation Device

A. Flexible Pneumatic Cylinder

Fig. 1 shows the construction of a low-friction type flexible pneumatic cylinder developed in the previous study [10]. The cylinder consists of a flexible tube as a cylinder and gasket, one steel ball as a cylinder head, and a slide stage with 12 steel balls which are set on the inner bore of the stage to press and deform the tube. The low-friction type means small friction between the slide stage and the flexible tube. The operating principle of the cylinder is as follows. When the supply pressure is applied to one side of the cylinder, the inner steel ball is pushed. At the same time, the steel ball pushes the slide stage and moves toward opposite side of the pressurized side while deforming the tube. The frictional force of the cylinder is relatively large compared with a typical rigid pneumatic cylinder. The minimum driving pressure of the cylinder is 94 kPa. This value is smaller than the case using the previous flexible pneumatic cylinder, that is 120 kPa [5].

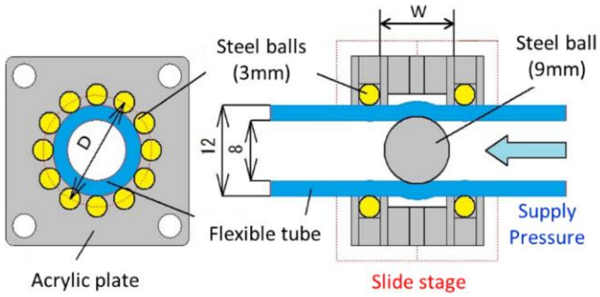

Figure 1. Low-friction type flexible pneumatic cylinder.

B. Flexible Spherical Actuator

Fig. 2 shows the appearance of the tested spherical actuator using two ring-shaped flexible pneumatic cylinders. In this case, the previous type flexible pneumatic cylinders were used. Two cylinders are intersected at right angle and each slide stage is fixed on each handling stage. The actuator can give a passive exercise for user's shoulders and arms while they hold both handling stages with hands.

Fig. 3 shows the transient view of the spherical actuator. In the experiment, the supply pressure of 450 kPa is applied. From Fig.3, it can be seen that the actuator can create the different attitudes easily. In addition, from the view of the movement of both arms, we found that the actuator gave the motion for not only wrists but also arms. Generally, the passive exercise such as a proposed motion is useful to recover the moving area of damaged joints and the function of nerves and muscles.

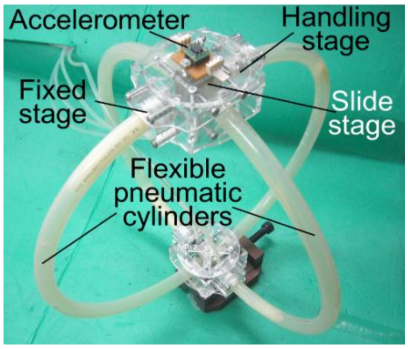

Figure 2. Spherical actuator using flexible pneumatic cylinders.

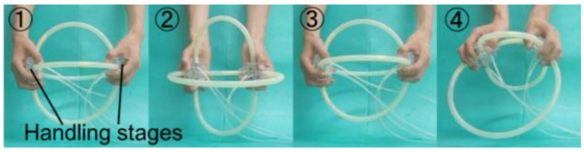

Figure 3. Movement of the tested spherical actuator.

III. Tetrahedral Structure Type Rehabilitation Device

A. Flexible Extension Type Actuator

The device using the spherical actuator can lead the passive exercise to upper limb by giving position change for both hands. However, if user wants to use it as a rehabilitation device for shoulder, the device cannot change its position (the absolute coordinate) while user holding it. If the device can change the absolute position, the device can gives passive exercise with larger moving area for shoulders and arms by combining the spherical actuator.

Therefore, in this study, a rehabilitation device that can change the coordinate of holding position is proposed. As a soft actuator used in the proposed device, an extension type flexible pneumatic actuator is proposed and tested. Figure 4 shows the view and schematic diagram of the proposed flexible extension type actuator. The tested actuator consists of a silicone rubber tube covered with a ruffled fabric sleeve made of nylon string and two acrylic end connectors with a supply port. The rubber tube has an inner diameter of 8 mm, outer diameter of 10 mm and length of 200 mm. The original length of the ruffled fabric sleeve in the stretched condition is 450 mm. The operating principle of the actuator is as follows. When the supplied pressure is applied to the actuator, the inner rubber tube extends toward radial and longitudinal directions. As the ruffled fabric sleeve can only deform toward longitudinal direction while preventing to extension toward radial direction, the actuator extension longitudinally. From the result of preliminary experiment, it is confirmed that the actuator can extend more than 2.5 times of the original length when the input pressure of 400 kPa is applied. The pushing force of the actuator while the actuator being pressurized is small because of its flexibility. However, the pulling force in the case of decompression is large. It is an elastic force of the rubber tube. The maximum of pulling force is about 19.5 N for the actuator displacement of 270 mm.

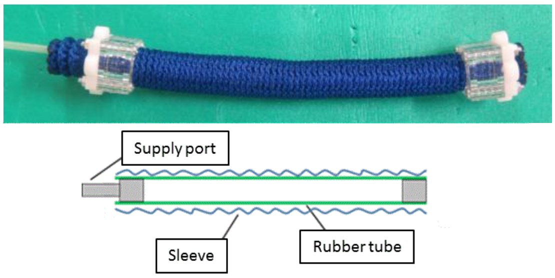

Figure 4. View and schematic diagram of tested flexible extension type. actuator

B.Construction of the Rehabilitation Device

Fig. 5 shows the construction of the tetrahedral structure type rehabilitation device that can change the coordinate of holding position. The device consists of a tetrahedral shaped frame, four flexible extension type actuators, and four wire type linear potentiometers [9] and a plastic ball with an outer a diameter of 100 mm. The frame consists of six aluminum pipes with a length of 1000 mm and an outer diameter of 15 mm and four plastic end connectors of pipes. Each end of the extend type actuator is connected to the plastic end connector of the frame by using nylon string and an iron hook. Each opposite end of the actuator is connected to the ball by using iron steel wire. The operating principle of the device is as follows. In the initial condition when no supply pressure is applied to each actuator, each actuator give the pulling force to the ball toward each connected vertex of tetrahedron. It means that the ball is naturally located at the center of gravity of the tetrahedral flame in the neutral condition. When one or some actuators are pressurized, the activated actuators extend. At the same time, the activated actuators release pulling force to the ball according to applied pressure. By changing the pulling force of each actuator acted on the ball, the location of the ball is changed based on the force balance.

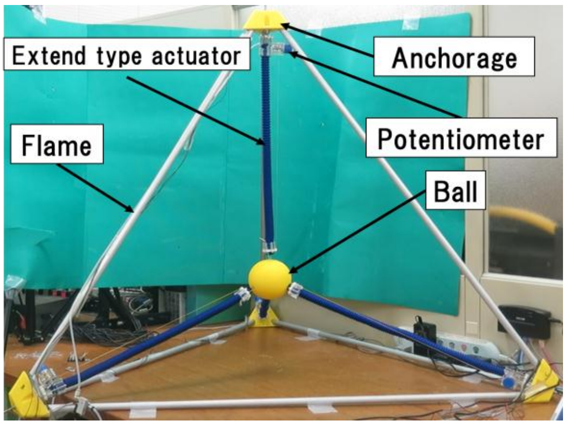

Figure 5. View of tetrahedral type rehabilitation device.

IV. Model of Device and Position Control System

A. Analytical Model of the Device

In order to control the position of the ball in the tetrahedral type rehabilitation device, an analytical model which can calculate desired length of each actuator from the desired coordinate of the ball is required. Figure 6 shows the analytical model of the device. In the model, the neutral position of the ball with no supplied pressure is defined as an origin. From the geometric relationship as shown in Fig. 6, each desired actuator length ra, rb, rc and rd from the desired coordinate P(x, y, z) of the ball are given by the following equations, respectively.

$$r_a = \sqrt{x^2 + y^2 + \left\{z - \frac{\sqrt{6}}{4}a\right\}^2} \tag{1}$$

$$r_b = \sqrt{\left\{x - (-\frac{1}{2}a)\right\}^2 + \left\{y - (-\frac{\sqrt{3}}{6}a)\right\}^2 + \left\{z - (-\frac{\sqrt{6}}{12}a)\right\}^2} \tag{2}$$

$$r_c = \sqrt{\left\{x - \frac{1}{2}a\right\}^2 + \left\{y - (-\frac{\sqrt{3}}{6}a)\right\}^2 + \left\{z - (-\frac{\sqrt{6}}{12}a)\right\}^2} \tag{3}$$

$$r_d = \sqrt{x^2 + \left\{y - \frac{\sqrt{3}}{3}a\right\}^2 + \left\{z - (-\frac{\sqrt{6}}{12}a)\right\}^2} \tag{4}$$

where a means the length of the one side of the tetrahedral frame. Actuator length ra, rb, rc and rd shows the length from each vertex A, B, C and D from the desired coordinate P(x, y, z), respectively. By using Eqs. (1) to (4), the desired length of each actuator can also be calculated.

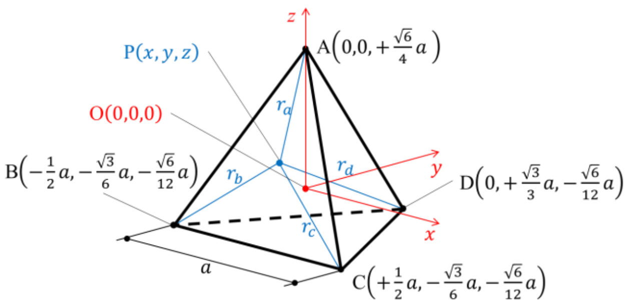

Figure 6. Analytical model to calculate each desired length of the actuator in tetrahedral structure type rehabilitation device.

B. Position Control System

Fig. 7 shows the schematic diagram of the position control system of the ball in the tetrahedral type rehabilitation device. The system consists of the tested device, four extension type actuators with wire type linear potentiometer, four quasi-servo valves [11], [12] to operate four actuators and an embedded controller (Renesas Design Vietnam Co. Ltd., SH7125). Each wire of the linear potentiometers is set parallel to the actuator through acrylic wire guide set on the actuator. The position control of the ball is done as follows. First, the embedded controller gets the desired coordinate of the ball as preprogramed sequence data and calculates the desired length of each actuator based on Eqs. (1) to (4).

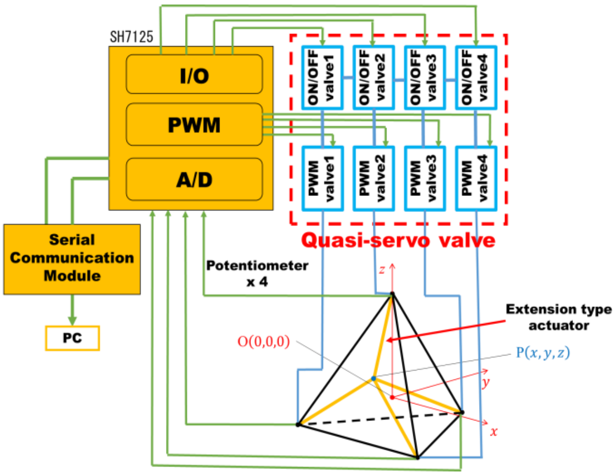

Figure 7. Schematic diagram of the position control of the ball in tetrahedral structure type rehabilitation device.

The controller also gets the output voltages from four wire type potentiometers and calculates the present length of each actuator. By comparing them, the deviation from the desired position can be calculated.

As a control scheme, the simple on/off control scheme is used. The sampling period is 5 ms. In the on/off control, the input duty ratio of PWM valves in quasi-servo valves are always set 100 %. The switching valves are only operated based on each deviation of the actuator. In addition, PID control schemes can be applied to the system by using the quasi-servo valves that can change the output flow rate analogically.

V. Controlled Results

Figure 8 shows the transient response of length of four extension type actuators for the multi-position control of the ball in the device. In the experiment, the desired coordinate position of the ball (x, y, z) = (0 mm, 0 mm, 0 mm), (50, 50, 50,), (50, -50, 50), (-50, -50, 50), (-50, 50, 50), (50, 50, -50), (50, -50, -50), (-50, -50, -50) and (-50, 50, -50) be changed every 10 seconds. In Fig. 8 the broken and solid lines show the desired displacement and the controlled displacement of extend type actuator A, B, C and D, respectively. From Fig. 8, it can be seen that each actuator can trace the desired length calculated by the desired coordinate of the ball.

Figure 9 shows the transient views of the position control of the ball when the simple on/off control scheme is applied. From Fig. 9, it can be found that some actuator extend too much and occur local deformation. The wire of the potentiometer can also bend according to the bending shape of the actuator by using wire guides set on the actuator. It means that the calculated coordinate of the ball is wrong while the wire of potentiometer is bending.

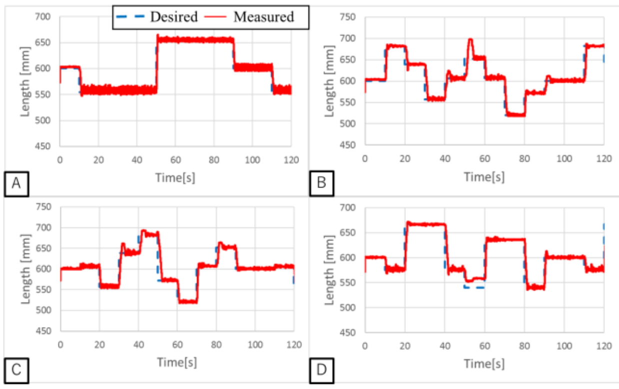

Figure 8. Transient response of length of each extension type actuator.

However, it is difficult to measure its length exactly when the actuator bends and deforms. Therefore, the checking method to find the case when the actuator extends too much is required. A fundamental idea of checking method is as follows.

Usually, when the control input calculated by the control scheme is positive, the actuator will be driven so as to extend its length. Then, the velocity of error of the actuator will become negative under the desirable condition that both length of the actuator and measured length using the potentiometer are same.

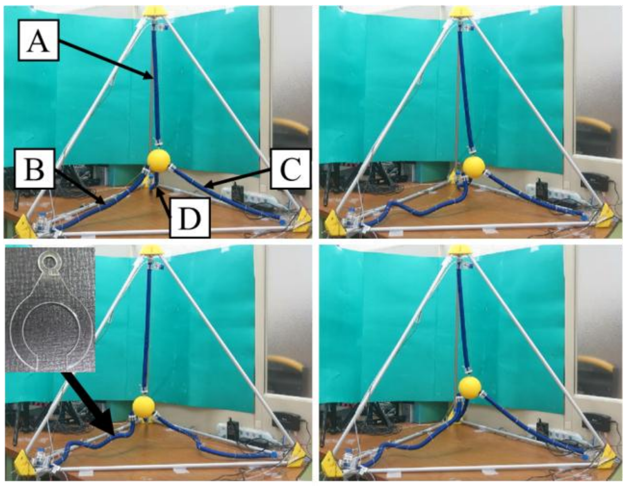

Figure 9. Transient views of the position control of the ball in the device.

However, when the undesirable situation when the actuator extends too much compared with wire length of the potentiometer occurs, the calculated velocity of error from the potentiometer's output becomes zero or positive. Therefore, the following additional driving condition of the actuator is added to a typical on/off control scheme. If the velocity of error is zero or positive under the condition when the control input is positive, the pulling motion is applied to the actuator.

Fig. 10 shows the transient view of the position control of the ball by using the on/off control scheme with additional checking method mentioned above. From Fig.10, it can be observed that all actuators keep straight.

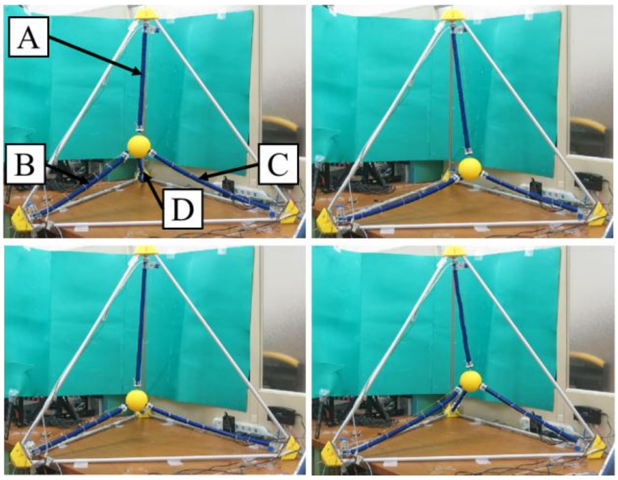

Figure 10. Transient views of the position control of the ball by using on/off control scheme with the additional checking method.

Fig. 11 shows the transient response of each length of the actuator for the multi-position control of the ball when the on/off control scheme with compensator for the local deformation of the actuator is applied. From Fig.11, compared with the previous result as shown in Fig.8, it can be seen that the oscillation around the desired position is caused by pulling action for preventing the actuator to extend too much. Although the small oscillation around the desired position occurs, we confirm that the position of the ball can trace the desired coordinate by applying the proposed simple on/off controller with compensator of actuator’s deflection.

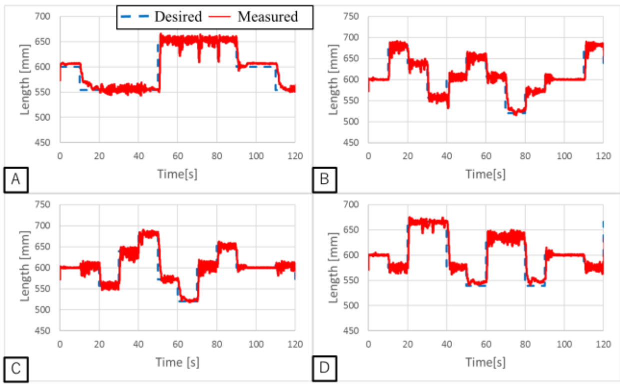

Figure 11. Transient response of length of each extension type actuator when on/off control scheme with compensator for deflection of the actuator is applied.

VI. Conclusions

This study aiming to develop the rehabilitation device that can change the absolute coordinate of holding position is summarized as follows.

As a soft actuator used in the proposed rehabilitation device, an extension type flexible pneumatic actuator is proposed and tested. We confirm that the tested actuator can extend more than 2.5 times of its original length.

As a rehabilitation device to give pulling and pushing motions to the handling stage, the tetrahedral type rehabilitation device using four flexible extension type actuators is proposed and tested. The analytical model to obtain each desired length of four actuators from the desired coordinate of the handling stage is proposed. The position control system of the handling stage in the tested device using the embedded controller and novel wire type potentiometers is also proposed and tested. The multi position control of the handling stage is carried out. As a result, it is confirmed that the position of the ball can trace the desired coordinate relatively well by applying the proposed simple on/off controller with compensator of actuator’s local deformation.

As future work, we are going to improve the position control performance of the device by applying the control scheme that can prevent the oscillation of handling stage.

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