# Development of Portable Rehabilitation Device Driven by Low-Cost Servo Valve Using Tap Water

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*Abstract*— **Wearable driving systems for labor assistance and rehabilitation, such as power assist suits, have received much attentions and many studies have been done actively. In this study, the final target is to develop a low-cost home rehabilitation device driven by fluidic actuators and low-cost control valves. In the device, the size and cost of control valves become serious concerns. In the previous study, to realize a home rehabilitation device, the flexible spherical actuator that was able to give passive exercise to patients was developed. To drive the actuator, control valves are required. However, a servo valve that can control flow rate in analogue way is very expensive compared with other elements in the pneumatic driving system. Therefore, a low-cost servo valve using buckled tubes was proposed and tested. This valve can control both gas and liquid flow. In this paper, the development of the spherical actuator driven by servo valves using buckled tubes is described as a low-cost home rehabilitation device. The construction and operating principle of the spherical actuator and the servo valve using buckled tube is also described. In addition, the position control using the tested devices is carried out.**

*Index Terms*— **Servo valve using buckled tubes, 4-port type servo valve, Tap water drive system, Portable rehabilitation device, Flexible spherical actuator.**

## I. INTRODUCTION

Recently, the wearable driving systems have gained considerable attention and many studies have been carried out actively [1-4]. They were developed as power assisting devices for nursing care [1], elderly [2] and worker [3] using pneumatic artificial muscles [4]. In this study, the final target is to develop a low-cost home rehabilitation device driven by pneumatic or hydraulic actuators where users can purchase it without financial assistance. In a fluidic driving wearable rehabilitation device, the size and cost of a control valve become serious concerns. Usually, the most expensive control device in the pneumatic and hydraulic driving systems is a control valve. In particular, a typical servo valve on the market is very expensive. A typical electro-magnetic servo valve has a complex mechanism for moving its spool while keeping a seal. The mechanism makes the valve more expensive. Therefore, miniaturization and fabrication of a low-cost servo valve are our great challenge. To decrease its mass, size and cost, the simple mechanism for valve opening is required [5-10]. Zhao developed small-sized quasi-servo valve using small-sized on/off valve [5]. Many researches developed small-size valves driven by vibration such as piezoelectric actuator [6], sound [7,8] and a vibration motor [9] was developed. In our previous study, a low-cost servo valve that could control the flow rate by changing the bending angle of the buckled tube was proposed and tested [11-15]. The positioning control of the pneumatic rubber artificial muscle using the valve was carried out [12]. The analytical model of the valve for optimal design was also proposed [13]. The pneumatic and water hydraulic position control system of the muscle using the valve were developed [14]. A 5-port type servo valve was also developed to drive a double acting type typical pneumatic cylinder [15]. In the next step, it is necessary to apply the tested valve to rehabilitation device at home. In addition, it is not so easy to get higher air pressure at home. On the other hand, it is easy to get water hydraulic power from tap water in Japan. Typical pressure of tap water is more than 250 kPa. Fortunately, the tested valve can control the flow rate of both gas (air) and liquid (water), because it has no mechanical moving part such as a spool in a flow passage. In this paper, as a lower-cost and more suitable home rehabilitation device, a spherical actuator equipped two 4-port type servo valves using buckled tubes driven by tap water is proposed and tested. The position control system using low-cost embedded controller is also developed. In addition, the position control using the tested devices is carried out.

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## II. FLEXIBLE SPHERICAL ACTUATOR

Fig. 1 shows the construction of a low-friction type flexible pneumatic cylinder developed in the previous study [16]. 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 operating principle 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 moves toward opposite side of the pressurized side while deforming the tube. The frictional force of the cylinder is relatively large compared with that of a typical rigid pneumatic cylinder. The minimum driving pressure of the flexible pneumatic cylinder is 94 kPa. This value is smaller than the case using the original flexible pneumatic cylinder, that is 130 kPa [17].

Fig. 2 shows the appearance of the tested spherical actuator using two ring-shaped flexible pneumatic cylinders [18]. In this case, the original flexible pneumatic cylinders [17] were used. Two cylinders are orthogonal and each slide stage is fixed on each handling stage. The actuator can be constructed at low cost. The material cost is about 20 USD. The actuator can give a passive exercise for user’s shoulders and arms while they hold both handling stages with hands. The actuator can give movement of the upper limb. Fig. 3 shows the transient view of the spherical actuator. The supply pressure is 450 kPa. 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, it gives the motion for not only wrist but also arms. Generally, the passive exercise such as proposed motion is useful to recover the moving area of joints and the function of nerves and muscles. On the hand, as a portable rehabilitation device, there is no device that can give the passive exercise for whole upper limb. The tested actuator can lead to move whole upper limb that includes shoulder and arm while holding it. On the market, there is only the device for hand. However, as patients must use it alone at home, it is better to observe a relative position between both handing stages to prevent crash accidents of patient’s hands.

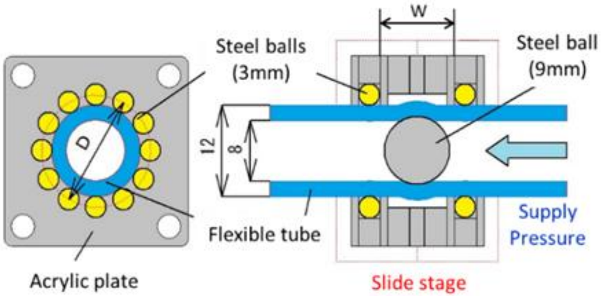


Figure 1. Low friction type flexible pneumatic cylinder.

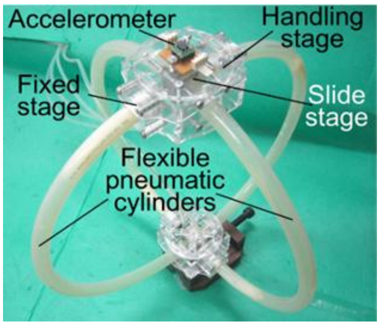


Figure 2. Spherical actuator using flexible pneumatic cylinders.

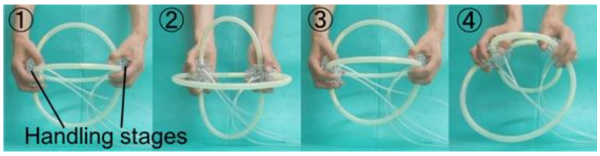


Figure 3. Movement of the tested spherical actuator.

## III. 4-PORT SERVO VALVE USING BUCKLED TUBES

### A. Construction

Fig. 4 shows the construction of the tested 4-port servo valve using buckled tubes developed in our previous study [15]. The tested valve consists of four buckled soft polyurethane tubes (SMC Corporation, TUS0425), four one-touch connecters (Koganei Corporation, US4M), two Y-shaped one-touch connecters (Koganei Corporation, UY4M), small-sized RC servo motor (Asakusa Giken Inc., ASV-15) and an acrylic rotational disk with connecter holders. To prevent interference between two sets of buckled tubes, one set of connectors is placed with gap of 7 mm in height on the rotational disk. The gap can realize the compact configuration with symmetric arrangement of buckled tubes and connectors. The mass of the valve is 73 g. The valve has a length of 90 mm, a width of 79 mm and height of 53 mm. From Fig. 4, the left and right output ports are port 1 and port 2, respectively.

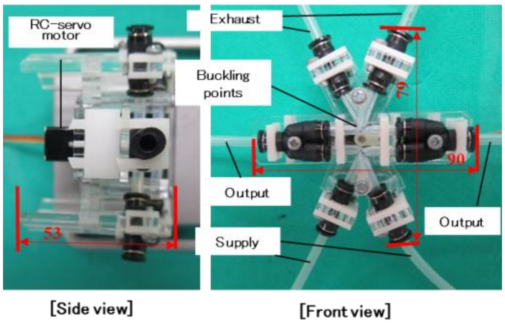
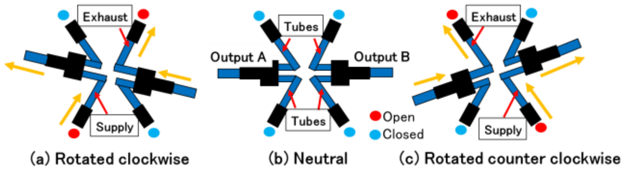


Figure 4. Construction of the 4-port valve.

### B. Operating Principle

Fig. 5 shows the operating principle of the tested valve. In the neutral position of the RC servo motor as shown in the Fig. 5(b), the sectional area of 4 buckled tubes for supply and exhaust at the buckled point are zero, that is, output A and B are closed. When the servo motor rotates clockwise as shown Fig. 5(a), the bending angles of left-side exhaust buckled tube and right-side supply buckled tube are decreased. At the same time, the bending angles of left-side supply buckled tube and right-side exhaust buckled tube are increased. In the condition, the sectional area of left-side supply tube and right-side exhaust tube have a certain sectional area that increases according to clockwise rotational angle of the RC servo motor. On the other hands, the left-side exhaust buckled tube and right-side supply buckled tube are closed completely. Thus, the operations that a fluid is supplied to output A and the fluid in output B is exhausted can be realized by single rotational motion of the RC servo motor. In opposite case when the motor rotates counter-clockwise as shown in Fig. 5(c), the fluid in output A is exhausted and a fluid is supplied to output B, simultaneously. The valve can also control the output flow rate from both output ports analogously. Thus, the valve can control both of supply and exhaust flow rate from two output ports synchronously by changing the rotational angle of the motor.



(a) Rotated clockwise (b) Neutral (c) Rotated counter clockwise

Figure 5. Operating principle of servo valve using buckled tubes.

### C. Output Flow Rate Characteristics

Fig. 6 shows the relations between the motor rotational angle of the RC servo motor and the output flow rate of the tested valve. In the experiment, air supply pressure of 500 kPa is applied to the supply port in the valve through a pneumatic regulator from an air compressor. The air flow rate was measured by using the digital flow meter (SMC Corporation, PFMB7201-C8-A-M). Based on a previous study [15], the tube length of 50 mm with the buckled points 13 mm are used where The buckled point distance is defined as a distance between the buckled point and the end of tube connected to the Y-shaped one-touch connector. Fig. 7 shows the relations between the motor rotational angle of the RC servo motor and the output flow rate of the tested valve using tap water pressure. In the experiment, tap water with supply pressure of about 250 kPa is applied to the supply port of the valve. As a measuring method of flow rate, the amount of output water through the port was measured every 6 seconds. In the case using pneumatic power as shown in Fig. 6, it can be seen that the valve of port 1 has an overlap zone between +7 deg. and -7 deg. In the case of port 2, there is an overlap zone between +3 deg. and -8 deg. The maximum flow rate of the valve is about 50 litter/minute. In the case using tap water as shown in Fig. 7, the valve of port 1 has an overlap zone between +6 deg. and -11 deg. In the case of port 2, the valve has an overlap zone between +3 deg. and -6 deg. The maximum flow rate of the valve using tap water is about 1 litter/minute. Compared with results using air and tap water, it can be seen that there is not so big differences about dead zones, but the maximum flow rate in both conditions is much different. Because of the difference of fluid viscosity between air and water, the maximum flow rate is different. It can be concluded that the overall characteristics of output flow rate of the valve using both air and water are similar because they have almost same dead zone. It means that the valve can be applied to both pneumatic and water hydraulic driving system by only changing the control scheme and control gains.

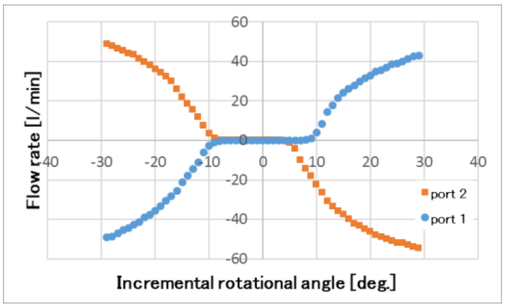


Figure 6. Relation between motor rotational angle and output flow rate of the valve in case using compressed air.

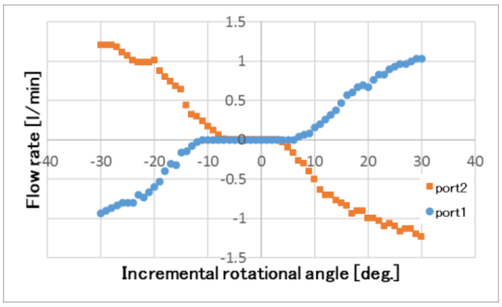


Figure 7. Relation between motor rotational angle and output flow rate of the valve in the case using tap water.

## IV. PORTABLE REHABILITATION DEVICE

### A. Flexible Spherical Actuator with Built-in ServoValve

A pneumatic driving system has many advantages; clean, light-weight, inexpensive, compliant and so on. However, it needs an air compressor or compressed air tank as an energy source. On the other hand, water hydraulic energy can be easily obtained from a tap water for a home rehabilitation device. In the next step, therefore, the development of a rehabilitation device driven by tap water will be considered. Fig. 8 shows a flexible spherical actuator with built-in 4-port type servo valves using buckled tubes. Two 4-port type servo valves are mounted on both handling stages of the spherical actuator. Two output ports in each valve are connected to both chambers of each flexible pneumatic cylinder. By this method, one valve can control the position of one cylinder for $x$ or $y$ direction independently. As a result, it can be realized the compact rehabilitation device with the built-in valves that it can be easy to carry it. The tested device also has 3D coordinate measuring device [19] mentioned later. Thus, the device has a length of 320 mm and height of 440 mm. The whole mass of the device including actuators, valves and sensors is not so heavy, that is 840 g. It means that the patient can hold and use the device while rehabilitation.

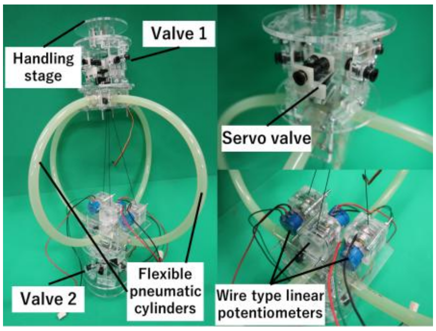


Figure 8. Flexible spherical actuator with built-in servo valve.

### B. *3D Coordinate Measuring Device*

Fig. 9 shows a 3D coordinate measuring device using three wire type linear potentiometers developed in our previous study [19]. The wire type linear potentiometer as shown in Fig. 10 consists of a helical potentiometer (BOURNS Co. Ltd., 3590S-A26-104L) that can measure 10 times rotational angle, a clockwork wire spool with diameter of 10 mm and a nylon wire with diameter of 1 mm. The maximum length for measurement is about 420 mm. The resolution of the potentiometer using 10-bit A/D converter is 0.411 mm. In the device, the end of wire of each potentiometer are connected each other. Each wire outlet from the potentiometer are arranged so that each distance from the measuring origin is kept at a distance *d* of 35 mm as shown in Fig. 9.

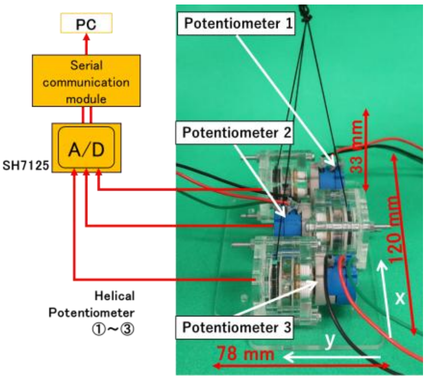


Figure 9. 3D coordinate measuring device.

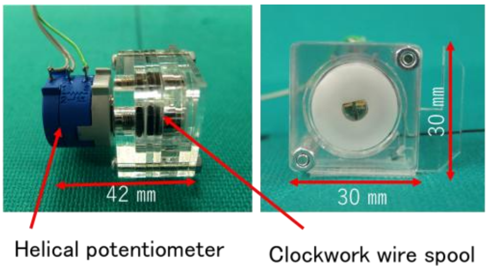


Figure 10. Wire type linear potentiometer.

Fig. 11 shows the measuring model of the device. From a geometric relationship, following equations related to the distance *d* and coordinate of measuring point (*x*, *y*, *z*) can be obtained.

$$D_1^2 = (x-d)^2 + y^2 + z^2 \tag{1}$$

$$D_2^2 = x^2 + (y-d)^2 + z^2 \tag{2}$$

$$D_3^2 = (x+d)^2 + y^2 + z^2 \tag{3}$$

(4) to (6) are derived from (1) to (3).

$$x = \frac{1}{4d}\left(D_3^2 - D_1^2\right) \tag{4}$$

$$y = \frac{1}{4d}\left(D_3^2 - 2D_2^2 + D_1^2\right) \tag{5}$$

$$z = \sqrt{D_3^2 - (x+d)^2 - y^2} \tag{6}$$

From (4) to (6), it can be seen that the coordinate can be obtained by measuring each distance $D_1$, $D_2$ and $D_3$.

The cost of wire type potentiometer is cheap, that is around 9 US dollars. The estimated cost of the whole 3D measuring device using three tested potentiometers is about 27 US dollars. We can realize the low-cost 3D coordinate measuring device with material cost of less than 30 US dollars.

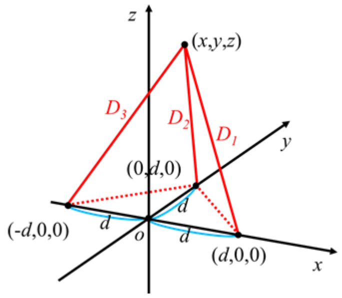


Figure 11. Measuring model of the device.

### C. *Sequential Control System Using Air Pressure*

As a preliminary experiment, the driving test of the device using air pressure is carried out. Fig. 12 shows the schematic diagram of the sequential control system using the tested spherical actuator. The system consists of the spherical actuator with the built-in 3D coordinate measuring device, two servo valves using buckled tubes and an embedded controller (Renesas Electronics Co., SH7125). The sequential control of the handling stage is done as follows. The embedded controller gives operational signal to drive the valves through I/O port based on sequential operation data. The controller also gets voltages from three wire type potentiometers in the coordinate measuring device through 10-bit A/D controller as a monitoring for attitude of the device. In the embedded controller, the coordinate of the handling stage is calculated from output voltages of three potentiometers based on the measuring model as shown in Fig. 9. In the experiment, the supplied air pressure of 400 kPa is applied to the valves. The actuator is operated by sequential control one by one in *x* and the *y* axis directions. Figs. 13 and 14 show experiment results on *x* and *y* axis. On both figures, red and blue lines show the operational signal for each valve and displacement of cylinder for *x* and *y* axis direction, respectively. From Figs. 13 and 14, it can be found that the displacement can be measured with both *x* and *y* axis coordinates. The valve operation was decided so that handling stages can move around + or – 100 mm toward *x* or *y* axis direction. And it was confirmed that handling stages of tested device can move for the displacements of approximately 120 mm to -100 mm in *x* axis direction, and approximately 80 mm to - 90 mm in *y* axis direction. In addition, it can be seen that the measured displacement on the *y* axis coordinate shows more oscillation than that on the *x* axis coordinate. However, by using this valve, the double acting motion of the double acting type actuator and the braking motion by blocking both pressure chambers can be realized. As a result, it can be concluded that the rehabilitation device that can give passive exercise by using a light-weight, compact and inexpensive mounting type valve can be developed.

In the next section, an attitude control of the tested rehabilitation device using tap water is discussed.

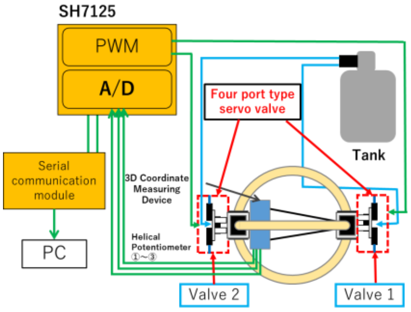


Figure 12. Schematic diagram of sequential control system.

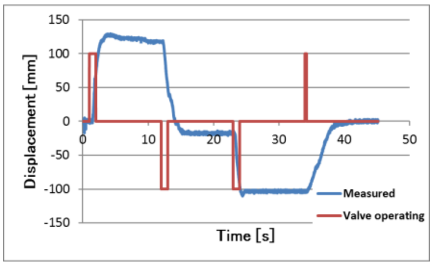


Figure 13. Sequential control result of x axis.

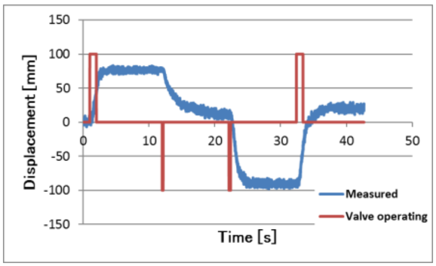


Figure 14. Sequential control result of y axis.

### *D. Attitude Control System Using Tap Water*

Fig. 15 shows the schematic diagram of the position tracking control system using the tested spherical actuator by using tap water. The system construction is almost same as the previous system as shown in Fig. 12. Compared with the previous system using air pressure, servo valves are connected to tap water supply pipe. The tracking control of the handling stage is done as follows. First, the embedded controller gets voltages from three wire type potentiometers in the coordinate measuring device through 10-bit A/D controller. In the controller, the coordinate of the handling stage is calculated from output voltages of three potentiometers based on the measuring model as shown in Fig. 9. In the control, coordinate *x* and *y* axis are only used as feedback signal. The control input for the tested servo valves, that is duty ratio of PWM signal with the period of 20 ms, are also calculated from the deviation of *x* and *y* axis coordinate from desired position. These PWM signal are given to RC servo motors in the tested servo valves through PWM ports in the embedded controller.

Figs. 16 and 17 show transient responses of the *x* coordinate and *y* coordinate of handling stage. In Figs. 16 and 17, the broken and solid lines show the desired and controlled position, respectively. In the experiment, the tap water supply pressure of about 250 kPa is applied to the valve. The tracking control toward *x* and *y* directions was only carried out. Each desired position is changed every 20 seconds. The sampling period of the control is 5 ms. As a control scheme, the following typical PID controller for *x* and *y* axis were used.

$$D_x(i) = k_P \cdot e_x(i) + k_D \cdot \{e_x(i) - e_x(i-1)\} + k_I \cdot \sum e(i) + D_C \cdot \operatorname{sign}(e(i)) \tag{7}$$

$$D_y(i) = k_P \cdot e_y(i) + k_D \cdot \{e_y(i) - e_y(i-1)\} + k_I \cdot \sum e(i) + D_C \cdot \operatorname{sign}(e(i)) \tag{8}$$

where, $D_x(i)$, $D_y(i)$, $e_x(i)$, $e_y(i)$, $k_{P,}$ $k_D$, $k_I$ and $D_c$ mean the duty ratio, error for *x* and *y* direction, proportional gain, differential gain and integral gain, the compensator for overlap zone of the valve, respectively. *i* means the discrete time per 1 step and *i*-1 means the data before one sampling time. The input duty ratio for the servo motor is obtained by adding the initial duty ratio of the neutral position to the calculated $D_x(i)$ and $D_y(i)$. These control parameters are selected by trails and errors. From Fig. 16, the small oscillation around desired position is occurred. However, the tested actuator can reach the desired position and can be held at the desired position within standard deviation of 3.4 mm. In addition, the oscillation at the beginning of the control is caused by the static frictional force. From Fig. 17, it can be seen that a relatively large oscillation around desired position is occurred compared with that on *x* axis. However, the tested actuator can be held near the desired position within standard deviation of 3.5 mm. As a result, it can be confirmed that the tested actuator can control the positions both *x* and *y* axis and can trace the desired position by using proposed low-cost servo valves.

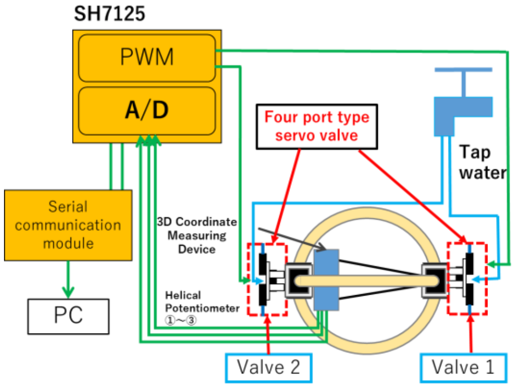


Figure 15. Schematic diagram of position tracking control system.

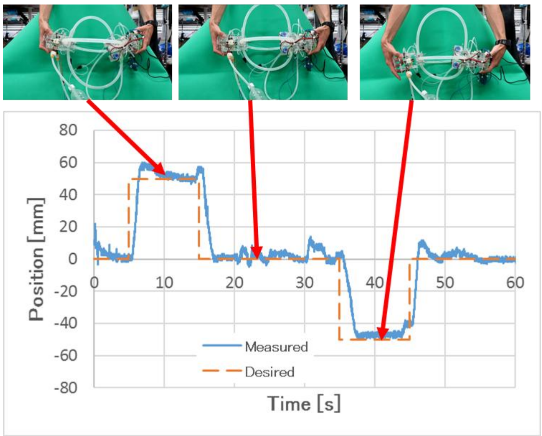


Figure 16. Position control result of x axis.

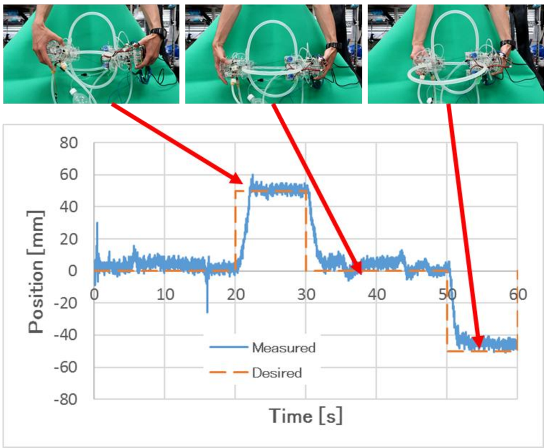


Figure 17. Position control result of y axis.

## V. CONCLUSIONS

This study aiming to develop the low-cost home rehabilitation device that can be easily used at home can be summarized as follows.

The portable rehabilitation device with built-in low-cost 4-port type servo valves using buckled tubes was proposed and tested. To confirm the performance of the tested device, sequential attitude control of the device using the tested valve was carried out by using air pressure. As a result, by using 3D coordinate measuring device, the displacement of handling stage on the device can be measured with both $x$ and $y$ axis coordinates. It can be confirmed that the home portable rehabilitation device can be constructed by using low cost servo valves. And passive exercise motion using the device can be realized.

In order to develop more user-friendly rehabilitation device at home, the portable rehabilitation device driven by tap water pressure was proposed and tested. The attitude control of the device based on measuring coordinate of handling stages was also carried out. As a result, the device can trace the desired position. It can be confirmed that the attitude control of the tested device can be realized by using tap water. It can be also confirmed that the tested low-cost servo valve is valid to apply the portable rehabilitation device driven by air pressure or tap water.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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