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Development of Wearable Wrist Rehabilitation Device Using Flexible Pneumatic Cylinders and Embedded controller

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Abstract. Recently, the rehabilitation devices using a soft pneumatic actuator for disabled are actively researched and developed because of the insufficient number of PT. In the previous study, the wrist rehabilitation device using flexible robot arm that consisted of three flexible pneumatic cylinders was proposed and tested. In this study, the wearable wrist rehabilitation device is proposed and tested. The attitude control based on the analytical model of the device is also carried out. As a result, it is confirmed that the device can trace the desired position in the condition when a human wears the device.

Keywords: *Wearable Wrist Rehabilitation Device; Flexible Pneumatic Cylinder; Embedded Controller*

I. Introduction

According to aging society and decreasing birth rate [1], lack of welfare workers and physical therapists ("PT" for short) becomes serious concern. Rehabilitation devices using soft pneumatic actuators for disabled are actively researched and developed [2-5]. In a previous study, a wrist rehabilitation device using flexible robot arm that consists of three flexible pneumatic cylinders was proposed and tested [6]. The attitude control of the robot arm while the hand is being put on the robot arm was carried out [7, 8]. The robot arm with simple back drivability was also developed [9]. In both cases, the hands of patients must be put on the robot on the table. It is difficult to use it while lying down. In the next step, a wearable type rehabilitation device for wrist is required. In this study, a wearable wrist rehabilitation device using improved flexible robot arm that can attach with human hand and arm. The attitude control of the device while wearing on human arm is carried out. In addition, the improvement of attitude control system of the device using an embedded controller and two accelerometers is investigated. The flexible pneumatic cylinder is a kind of new soft actuator. This actuator has an advantage of flexibility based on the air compressibility and the usage of flexible tube. We believe that the flexible cylinder contribute to extend the robotics application fields as proposed in this paper.

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II. Previous Flexible Robot Arm for Wrist Rehabilitation

Fig. 1 shows the flexible robot arm for wrist rehabilitation and construction of flexible pneumatic cylinder that were developed in our previous study [6]. The robot arm consists of two round stages and three flexible pneumatic cylinders. The cylinder consists of a flexible tube as a cylinder, the steel ball as a cylinder head, and a slide stage. The slide stage has two brass rollers set on the inner bore of the stage to press and deform the tube. The steel ball is held by two slide stages from both sides of the ball. When the pressure is applied to one side of the cylinder in the robot arm, the tube is moved up and down while holding the slide stage. Each flexible pneumatic cylinder is arranged so that the central angle of two adjacent slide stages becomes 120 deg. on the round stage. An end of each flexible cylinder is fixed in the upper stage. The robot arm has the outer diameter of 100 mm and the length of 250 mm. The total mass of the robot arm is 380 g. The operating principle of the arm is as follows. When the pressure is supplied on the three top ends of the cylinders, the robot arm extends or moves upward. On the other hand, the robot arm will contract or move downward when the pressure is supplied on the three bottom ends of the cylinders. The bending motion of the arm can be obtained when one cylinder is fixed and the others are pressurized from bottom ends. By this method, the arm is bent toward opposite side of the fixed cylinder. The robot arm can also be bent to every direction [7-9]. In a rehabilitation, the arm is used while the upper stage of the robot is grasped by a human hand. However, the device cannot be used while lying down. Therefore, it is necessary to develop a wearable type wrist rehabilitation device.

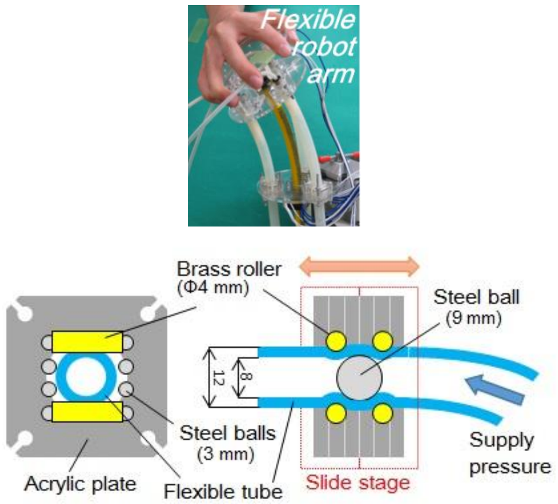

Figure 1. View of flexible robot arm and the inner construction of flexible pneumatic cylinder.

III. Wearable Wrist Rehabilitation Device

Fig. 2 shows the tested wearable type wrist rehabilitation device using flexible pneumatic cylinders. The fundamental construction of the device is similar to the flexible robot arm. Compared with the robot arm, the device is set so as to inverse the upper and lower stages. The end stage that is connected with the slide stages of the flexible pneumatic cylinders has a handle. The other stage that is connected with ends of the cylinders has a hole with inner diameter of 100 mm so as to insert a human arm. In other words, the patient arm passes through the holes of the base stage, and the patient holds the handle while its working. Each cylinder is also arranged with radius of 87.5 mm every 120 deg. from the center of the disk. The device also has the attitude control system that consists of an embedded controller (Renesas Co. Ltd., SH7125) and six quasi-servo valves [9] that each valve consists of two on/off control valves. The embedded controller and three quasi-servo valves are mounted on the base stage. On the end stage, there are three quasi-servo valves and an accelerometer for measuring the inclined angle of the stage. To supply the compressed air from base to end stage, a coil type tube that covers on a flexible pneumatic cylinder is used. By this method, the device requires only an electric power cable and an air supply pipe to drive it. The device has the outer diameter of 200 mm and the length of 420 mm. The total mass of the device including a controller and six quasi-servo valves is 1.14 kg.

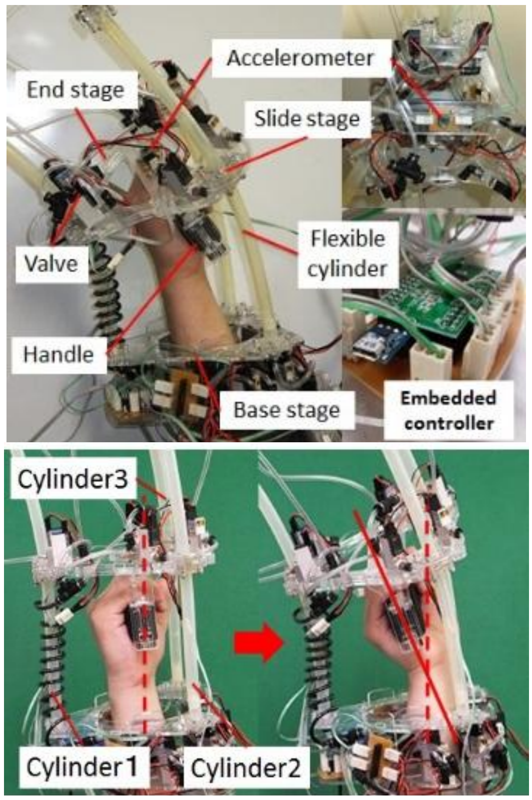

Figure 2. Construction of wearable wrist rehabilitation device using flexible pneumatic cylinders.

IV. Analytical Model and Attitude Control of Device

Fig. 3 shows the definition of the cylinder length and an analytical model of the flexible robot arm, that is wearable rehabilitation device. In this model, the shape of the flexible pneumatic cylinder is assumed to be a circular arc when the device is bent. From the center of the device, the bending angle from X axis is called a bending direction angle *α* while the bending angle *β* is defined as the angle between the normal vectors from the center of the upper surface of the Z axis of robot arm. From the geometric relationship, the following equations approximately cylinder length L_1, L_2, L_3 and the radius of curvature *R* can be obtained.

$$L_1 = (R - r \cdot \cos\alpha) \cdot \beta \tag{1}$$

$$L_2 = \left\{R - r \cdot \cos\left(\frac{2\pi}{3} - \alpha\right)\right\} \cdot \beta \tag{2}$$

$$L_3 = \left\{R - r \cdot \cos\left(\frac{4\pi}{3} - \alpha\right)\right\} \cdot \beta \tag{3}$$

$$R = L/\beta \tag{4}$$

where *L* means the length of human arm, and *r* (= 87.5 mm) is the distance from the center to the cylinder. Angles *α* and *β* can be obtained from the output voltage of the accelerometer.

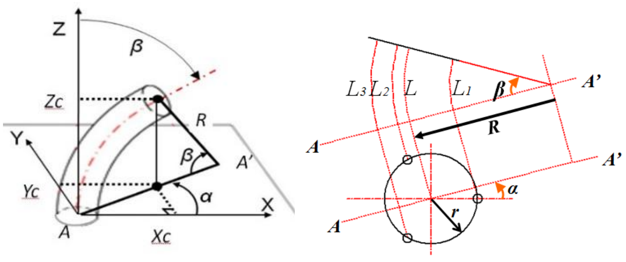

Figure 3. Analytical model of wearable device (flexible robot arm).

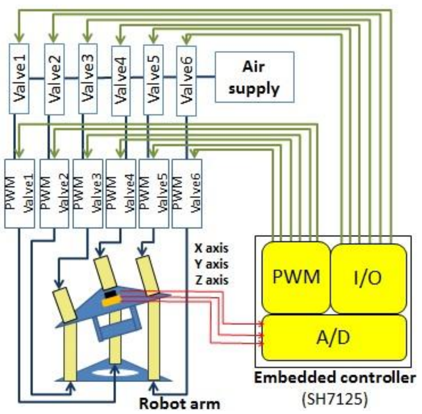

Figure 4. Schematic diagram of control system.

Fig. 4 shows the schematic diagram of control system of the wrist rehabilitation device. In the control, a following PID control scheme is used.

$$u_{j(k)} = \mathrm{K_p} \cdot d_{j(k)} + \mathrm{K_d} \cdot \left(d_{j(k)} - d_{j(k-1)} \right) + \mathrm{K_i} \cdot \sum d_{j(k)} \tag{5}$$

Switching valves

$$\begin{array}{lll} \text{End stage : OFF,} & \text{Base stage : ON} & (u_{j(k)} > 0) \\ \text{End stage : ON,} & \text{Base stage : OFF} & (u_{j(k)} < 0) \\ \text{End stage : OFF,} & \text{Base stage : OFF} & (u_{j(k)} = 0) \end{array}$$

where $d_{j(k)}$ and $u_{j(k)}$ mean the current deviation of cylinder displacement and the differential input duty ratio for PWM valves, respectively. As an input duty ratio, 22.5% is added to compensate the dead zone of PWM valves [10]. Subscript *j* shows the cylinder number 1, 2, and 3. The control parameters of $\mathrm{K_p}$ = 3.5 %/mm, $\mathrm{K_d}$ = 2.5 %/mm, and $\mathrm{K_i}$ = 0.05 %/mm were decided by trial and error.

The system consists of the flexible robot arm using three flexible pneumatic cylinders, an accelerometer, an embedded controller (Renesas Co. Ltd., SH7125) and six quasi-servo valves. The quasi-servo valve consists of two on/off type valves that one is a switching valve for supply or exhaust and the other is PWM controlled valve for adjusting flow rate. The attitude control of the device is as follows. First, the embedded controller gets the output voltages from the accelerometer through A/D converter. Each length of the flexible pneumatic cylinder is calculated based on the model as shown in Fig. 3. The embedded controller also calculates the deviation from the desired position for each cylinder. The quasi-servo valves are driven according to the control scheme. The desired position is set on the embedded controller previously.

Fig. 5 shows the transient response of each cylinder length in attitude control. In the control, PID control scheme with sampling period of 7 ms was used. The length *L* was set to be 150 mm. In Fig. 5, the broken and solid lines show the desired and controlled length of each cylinder, respectively. It can be seen that the cylinder reach the desired length within approximately one second even if the force from the human wrist is applied to the device as a load. It can be confirmed that the tested device is useful to apply to a self-rehabilitation device.

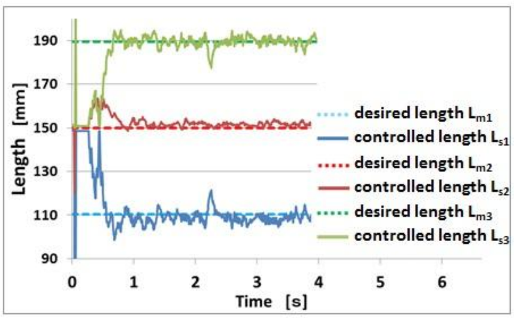

Figure 5. Transient response of cylinder length in attitude control.

Fig. 6 shows the transient response of each cylinder length in multi-position control. It can be seen that the cylinder trace the desired length. For changing desired position, it reaches at the desired position within approximately one second even if the force from the human wrist is applied to the device as a load.

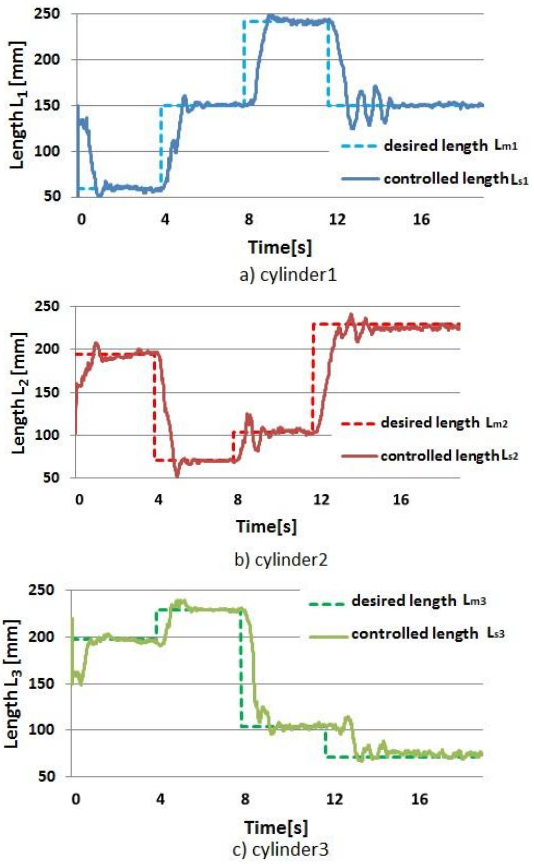

Figure 6. Transient response of cylinder length in multi-position control.

V. Improvement of Wearable Wrist Rehabilitation Device

In order to use the tested device while lying down, the improvement of attitude control system of the device is required. In the next step, the improvement of attitude control system of the device using an embedded controller and two accelerometers is carried out. Fig. 7 shows the schematic diagram of the control system of the improved wearable wrist rehabilitation device. The fundamental construction of control system is similar to the previous device. Compared with the previous system, an accelerometer is added and set on the base stage. The attitude control of the device is carried out as follows. The embedded controller gets the output voltages from two accelerometers through A/D converter. From A/D value of *x*, *y*, and *z* direction of each accelerometer, a bending direction angle α and the bending angle β of each stage can be calculated. Differential bending angles α and β are given by (6) and (7), respectively.

$$\alpha = \alpha_e - \alpha_b \tag{6}$$

$$\beta = \cos^{-1} (\cos\beta_e \cdot \cos\beta_b - \sin\beta_e \cdot \sin\beta_b \cdot \cos\alpha) \tag{7}$$

where subscripts *e* and *b* mean the end and base stages, respectively. Equation (7) can be obtained by the geometrical relationship between the base stage and the end stage. When $\alpha_e = \alpha_b$, that is $\alpha = 0$, the bending angle β can be expressed by the difference $\beta_e - \beta_b$. This is obviously obtained by (7). By using the calculated α and β, each length of the flexible pneumatic cylinder is calculated by (1) to (4). The embedded controller also calculates the deviation from the desired position for each cylinder. The quasi-servo valves are driven according to the PID control scheme.

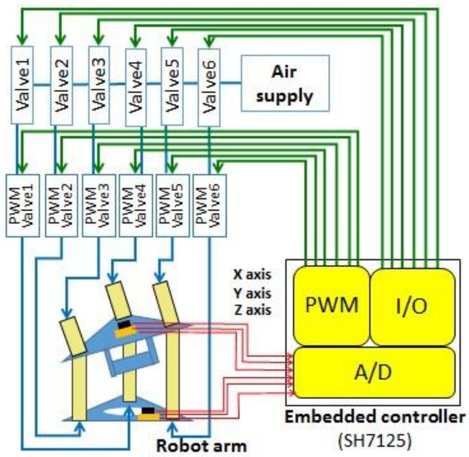

Figure 7. Schematic diagram of improved control system.

Fig. 8 shows the transient response of each cylinder length in multi-position control. In the experiment, the base stage has the inclined angle of approximately 20 deg. from the horizontal plane as an initial condition. In the control, PID control scheme with sampling period of 7 ms. The control parameter gains of K_p = 3.5 %/mm, K_d = 3.5 %/mm, and K_i = 0.3 %/mm was used. The same desired positions as the previous experiment were given. In Fig. 8, the broken and solid lines show the desired and controlled length of each cylinder, respectively. It can be seen that the cylinder trace the desired position. As a result, it can be confirmed that the device give the motion to patient's wrist even if the patient's arm is not set parallel to the vertical plane. It can be observed that there are oscillation around the desired position. This seems to be caused by adding the accelerometer to the control system. The controlled performance can be improved by applying superior control scheme.

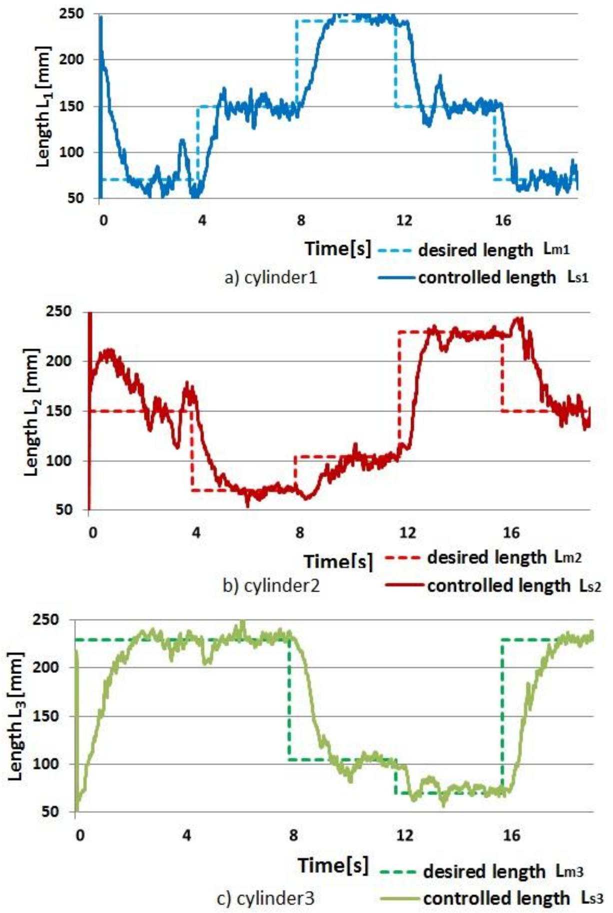

Figure 8. Transient response of cylinder length in multi-position control.

VI. Conclusions

The wearable wrist rehabilitation device using three flexible pneumatic cylinders, an embedded controller, six quasi-servo valves and an accelerometer is proposed and tested. The attitude control based on the analytical model is also carried out. As a result, it is confirmed that the device can trace the desired position within approximately one second in the condition when a human wrist works as a load. The improvement of attitude control system of the device using an embedded controller and two accelerometers was carried out. The measuring system of differential bending angle between the base and the end stage of the device is also constructed in the built-in embedded controller. By using this measuring system, the attitude control of the improved device can be realized. As a result, it can be confirmed that the device can give the motion to patient's wrist even if the patient's arm is not set parallel to the vertical plane.

VII. Acknowledgements

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