International Journal of Mechanical Engineering and Robotics Research Vol. 6, No. 3, May 2017

Development of Simplified Wearable Wrist Rehabilitation Device Using Low-Friction Type Flexible Pneumatic Cylinders

Wataru Kobayashi, Jie Guo, Tetsuya Akagi, Shujiro Dohta, and Naoki Kato
Department of Intelligent Mechanical Engineering, Okayama University of Science, Okayama, Japan
Email: kobayashi@are.ous.ac.jp, chinjap19@gmail.com, {akagi, dohta}@are.ous.ac.jp, t16rm02kn@ous.jp

***Abstract*— According to development of medical treatment, the population of the elderly is increasing. Therefore, rehabilitation devices using soft pneumatic actuators for the disabled are actively researched and developed because of insufficient number of physical therapists (PT). The purpose of this study is to develop a home rehabilitation device that can be used by him/herself without PT. In the previous study, the wearable wrist rehabilitation device using flexible pneumatic cylinders was proposed and tested. The attitude control based on an analytical model of the device was also carried out. In this paper, in order to reduce the burden of patients, the light-weight and low-cost device which has a simplified attitude control system with a dead zone and low-friction type cylinders is proposed and tested.**

***Index Terms*—wearable wrist rehabilitation device, low-friction type flexible pneumatic cylinder, simplified pneumatic driving system**

I. Introduction

According to aging society and decreasing birth rate [1], the lack of welfare workers and physical therapists becomes serious concern. Rehabilitation devices using soft pneumatic actuators for disabled have been 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 a human hand was being put on the robot arm was carried out [7]-[9]. The wearable wrist rehabilitation device that can be worn on patient's arm was also developed [10]. The device can be driven successfully. However, the device has a complex built-in pneumatic driving system using twelve on/off control valves.

In the next step, we aim to develop a more suitable and wearable home rehabilitation device that is light-weight and low-cost. In this study, to reduce the burden of patients, we develop a simplified device which is more compact and cheaper than the previous one. First of all, a low-friction type flexible pneumatic cylinder is proposed to make the movement of the device more smoothly. Secondly, the number of valves is reduced by half. Thirdly, the weight of the end and base stages is reduced. Finally, a simplified attitude control system with a dead zone of cylinder displacement is applied, because the oscillation is occurred due to on/off control of the valves and it is not suitable for rehabilitation.

II. Wearable Wrist Rehabilitation Device

Fig. 1 shows the tested wearable type wrist rehabilitation device using flexible pneumatic cylinders [10]. The device consists of two round stages and three flexible pneumatic cylinders. Fig. 2 shows a schematic diagram of the flexible pneumatic cylinder.

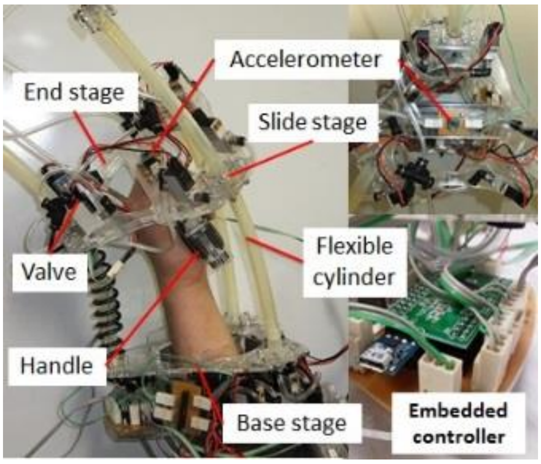


Figure 1. Construction of the previous wearable wrist rehabilitation device

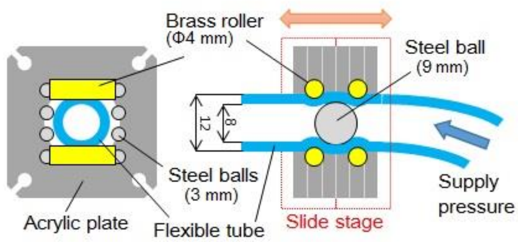


Figure 2. Schematic diagram of the previous flexible pneumatic cylinder

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

Manuscript received January 1, 2017; revised April 11, 2017.

doi: 10.18178/ijmerr.6.3.253-257

the stage to press and deform the tube. The steel ball is held by two slide stages from both sides of the ball. The end stage connected with the slide stages of the flexible pneumatic cylinders has a handle. The other stage connected with ends of the cylinders has a hole with inner diameter of 100 mm so as to insert a human arm. Each cylinder is also arranged with radius of 87.5 mm every 120 deg. from the center of the disk. The device also has an attitude control system. The system consists of an embedded controller (Renesas Co. Ltd., SH7125) and six quasi-servo valves [11] 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. The device has the outer diameter of 200 mm and the length of 420 mm. The total mass of the device including the controller and six quasi-servo valves is 1.14 kg. As a result of various experiments, we can confirm that the tested device can move successfully. However, in the control, an oscillation was occurred by the frequent operations of valves around desired position. This means that a dead zone in the control should be added.

III. Low-Friction Type Flexible Pneumatic Cylinder

In order to realize smooth motion of the device, it is necessary to reduce the frictional force in a flexible pneumatic cylinder. Fig. 3 shows the construction of a low-friction type flexible pneumatic cylinder. Compared with the previous cylinder [6], the slide stage of the improved cylinder has 12 steel balls which are 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 side of the ball. The operating principle of the cylinder is same as the previous one. The center diameter *D* of 14.8 mm is decided by the preliminary experiment. The experiment was carried out by changing the center distance *D* to investigate whether the steel ball can keep position between both slide stages, when the supply pressure of 500 kPa is applied. The distance *W* between steel balls affects the frictional force of the cylinder.

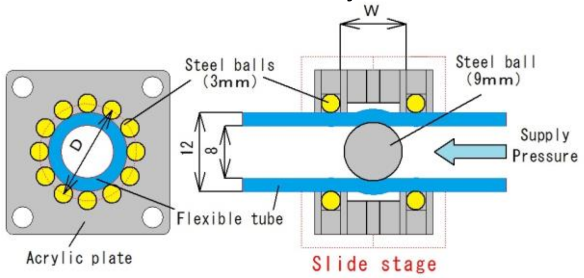


Figure 3. Schematic diagram of low-friction type flexible cylinder

Fig. 4 shows the relation between distance *W* of slide stage and the minimum driving pressure of the flexible pneumatic cylinder. In Fig. 4, the red, blue, and green lines show the maximum, average, and minimum values of the minimum driving pressure, respectively. From Fig. 4, when the distance *W* is set to 10 mm, it is confirmed that the measured minimum driving pressure is the smallest. In this situation, it can be seen that the inner steel ball is pushed by air pressure, and it pushes one side of the slide stage. Compared with the previous cylinder, the friction between the ball and slide stages is reduced and the minimum driving pressure of the cylinder is reduced from 120 kPa to 94 kPa.

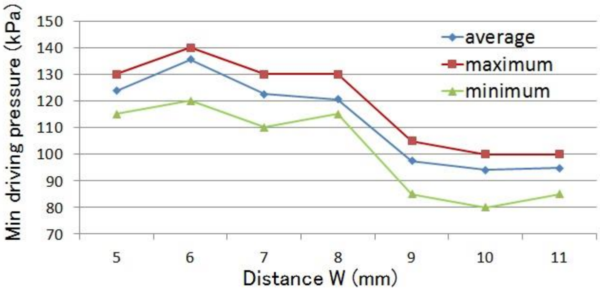


Figure 4. Relation between distance W and minimum driving pressure of low-friction type flexible pneumatic cylinder

IV. Simplified Wrist Rehabilitation Device

Fig. 5 shows the construction of the improved wearable wrist rehabilitation device using low-friction type flexible pneumatic cylinders. Compared with the previous device, the number of the valves is reduced from 12 to 6 in order to simplify the structure and control system of the device. By applying on/off control scheme with a dead zone, the oscillation around desired position is prevented. Note that the control performance of the proposed scheme is degraded. It is important for rehabilitation to prevent the oscillation of the device even if the control performance becomes worse. In experiments described later, the dead zone is set to ±12 mm of the desired position.

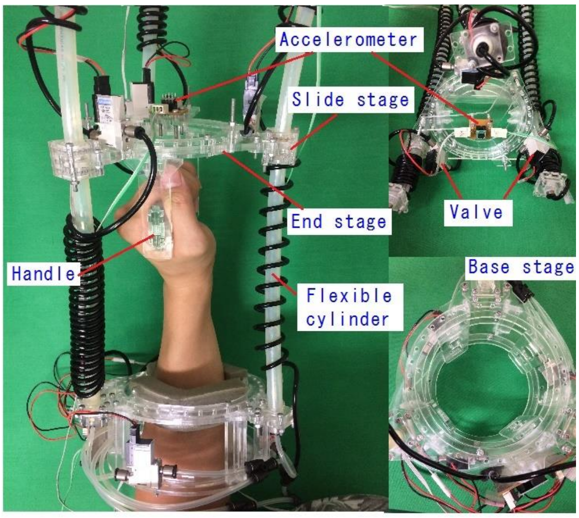


Figure 5. Construction of improved wearable wrist rehabilitation device using low-friction type flexible pneumatic cylinders

Three on/off valves are mounted on each stage. There is a coil type tube between the valve and the end of cylinder. In order to reduce the mass of the device, triangle-shaped acrylic stages are used. The end stage has a handle set on the stage. Users of the device can adjust the handle arbitrarily by turning it. Although the size of the device is almost same as the previous one, the whole mass of the device including the controller and six control valves is reduced from 1.14 kg to 0.9 kg.

Fig. 6 shows a schematic diagram of the control system of the improved wrist rehabilitation device. The system consists of the device using low-friction type cylinders, an accelerometer, an embedded controller (Renesas Co. Ltd., SH7125), and six on/off valves (Koganei Co. Ltd., G010E1). The attitude control of the device is done as follows. First, the embedded controller gets the output voltages from the accelerometer through A/D converter. Each length of the flexible pneumatic cylinders is calculated based on the analytical model [10]. The embedded controller also calculates the deviation from the desired position for each cylinder. On the other hand, the desired position is set on the embedded controller in advance. A simple on/off control scheme with dead zone of 12 mm is applied. The dead zone is decided by trials and errors so as to reduce the oscillation of the device.

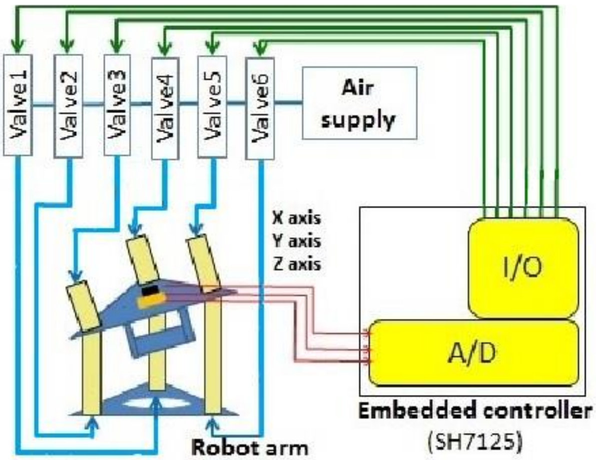


Figure 6. Schematic diagram of control system of improved device

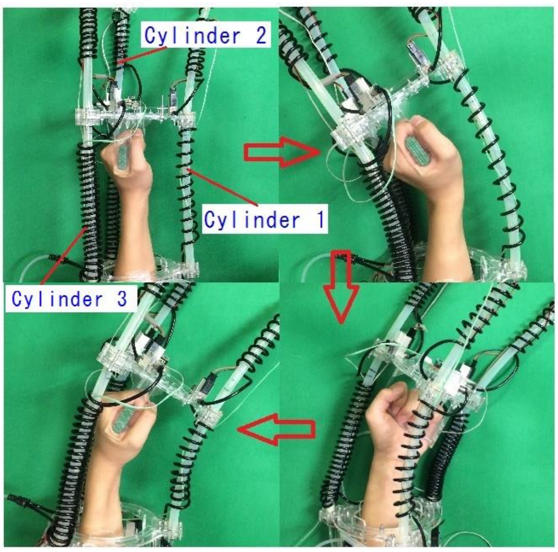
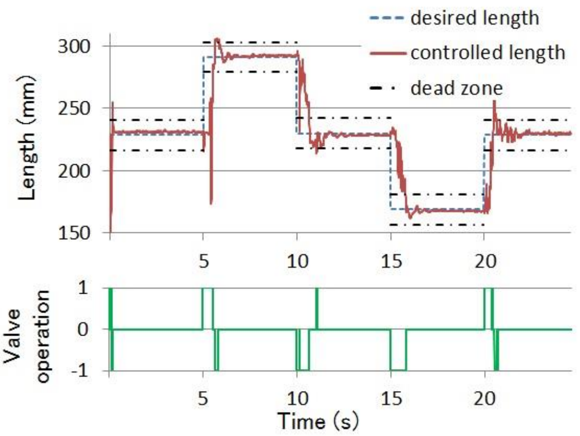


Figure 7. View of movement of wearable wrist rehabilitation device using low-friction type flexible pneumatic cylinders

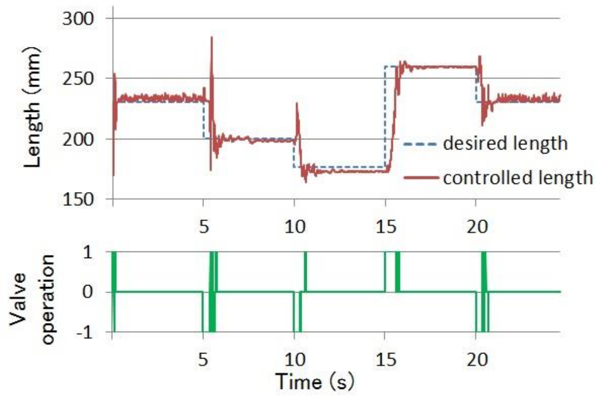
V. EXPERIMENTAL RESULTS

To examine the behavior of the tested device and the control performance of the proposed control scheme, an experiment of the attitude control is carried out. Fig. 7 shows the experimental view of movement of the improved wrist rehabilitation device using low-friction type flexible pneumatic cylinders. In the experiment, the desired position of each cylinder is changed every 5 seconds. It can be found that this device can bend the wrist toward three directions.

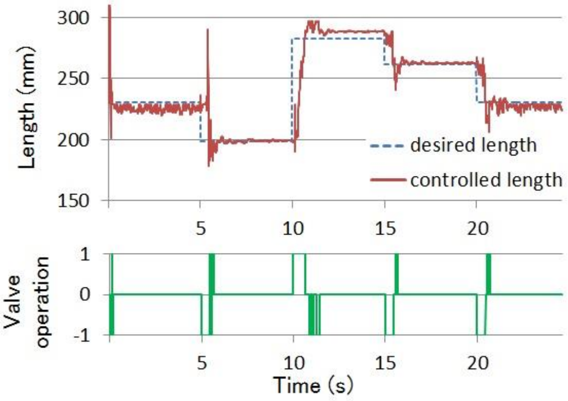
Fig. 8 shows the transient response of each cylinder length and valve operations in the attitude control with multi-position. In the experiment, the desired bending angle of 40 degrees was set. The bending direction angle was changed clockwise every 90 degrees. In Fig. 8, each blue dotted and red solid line shows the desired position and controlled position of the cylinders in the device, respectively. Each green line shows the valve operation in the control. Note that "1" means the valve which is mounted on the end stage is turned on, "0" means that both valves are turned off, and "-1" means that the valve which is mounted on the base stage is turned on. From Fig. 8, it can be seen that each cylinder traces the desired length well. It can be also found that the frequent valve operation does not occur and then the oscillation of the device is also prevented. Therefore, the smooth movements can be achieved.



a) Cylinder 1



b) Cylinder 2



c) Cylinder 3

Figure 8. Transient response of each cylinder length in multi–position control using the improved device.

VI. Conclusions

In order to reduce a burden of patient, the light-weight and compact device which has simplified an attitude control system with a dead zone and low-friction type cylinders was proposed and tested. Although the size of the device was almost same as the previous one, the total mass of the device including a controller and six control valves was reduced from 1.14 kg to 0.9 kg.

The wrist rehabilitation device using the improved flexible pneumatic cylinders was also proposed and tested. To prevent the oscillation of the device, a simplified attitude control scheme with the dead zone of ±12 mm was applied and then the experiment of the proposed control was carried out. As a result, it is confirmed that the device can be operated smoothly without oscillation.

As a future work, in order to improve the control performance of the device, we are going to develop a flexible displacement sensor that can measure the displacement of the flexible pneumatic cylinder directly.

Acknowledgment

This research was supported by the MEXT in Japan through a Financial Assistance Program for QOL Innovative Research (2012-2016) and a Grant-in-Aid for Scientific Research (C) (Subject No. 24560315 & 16K06202).

References

[1] Ministry of Internal Affairs and Communications, Statistics Bureau, Statistics, Population Estimates, Result of the Population Estimates, Monthly Report. Result of the Population Estimates. (2015). [Online]. Available: http://www.stat.go.jp/english/data/jinsui/tsuki/

[2] M. Ishii, K. Yamamoto, and K. Hyodo, “Stand-Alone wearable power assist suit -development and availability,” *Journal of Robotics and Mechatronics*, vol. 17, no. 5, pp. 575–583, 2005.

[3] J. Piquion, *et al*., “Robot-assisted gynecological surgery in a community setting,” *Journal of Robotics and Surgery*, vol. 3, no. 2, pp. 61–64, 2009.

[4] T. Noritsugu, M. Takaiwa, and D. Sasaki, “Development of power assist wear using pneumatic rubber artificial muscles,” *Journal of Robotics and Mechatronics*, vol. 21, no. 5, pp. 607-613, 2009.

[5] H. Kobayashi, T. Shiban, and Y. Ishida, “Realization of all 7 motions for the upper limb by a muscle suit,” *Journal of Robotics and Mechatronics*, vol. 16, pp. 504-512, 2004.

[6] T. Akagi and S. Dohta, “Development of a rodless type flexible pneumatic cylinder and its application,” *Transactions on Robotics and Automation of the JSME (C)*, vol. 73, no. 731, pp. 2108–2114, 2007. (in Japanese)

[7] T. Akagi, S. Dohta, F. Zhao, and T. Fujikawa, “Development and attitude control of flexible robot arm using flexible pneumatic cylinder with simple structure,” *International Journal of Automation Technology*, vol. 5, no. 4, pp. 523-530, 2011.

[8] M. Aiff, T. Akagi, and S. Dohta, “Control and analysis of robot arm using flexible pneumatic cylinder,” *Mechanical Engineering Journal*, vol. 1, no. 5, pp. 1-13, 2014.

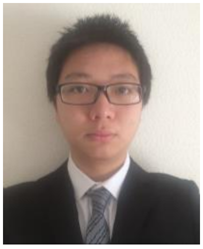
[9] T. Morimoto, T. Akagi, and S. Dohta, “Development of flexible haptic robot arm using flexible pneumatic cylinders with backdrivability for bilateral control,” *Lecture Notes in Electrical Engineering*, vol. 345, pp. 231-237, 2016.

[10] N. Kato, S. Dohta, T. Akagia, T. Morimoto, and Y. Soga, “Development of wearable wrist rehabilitation device using flexible pneumatic cylinders,” in *Proc. MATEC Web of Conference*, 2016.

[11] F. Zhao, T. Akagi, and S. Dohta, “Development of small-sized quasi-servo valve for flexible bending actuator,” in *Proc. CACS Int. Automatic Control Conference*, 2009, pp. 558-562.

Wataru Kobayashi is currently an assistant professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Shibaura Institute of Technology in 2015. His research interests are robust control theory and aqua drive system; especially rehabilitation and life support systems.

He is a member of The Japan Society of Mechanical Engineers, The Society of Instrument and Control Engineers, The Japan Fluid Power System Society, and The Society of Life Support Engineering.



Jie Guo, undergraduate student, studies in Okayama University of Science since 2013. His research topics are focused on Development of Simplified wearable wrist rehabilitation device using low-friction type flexible pneumatic cylinders.

Tetsuya Akagi is currently a professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Okayama University of Science in 1998.

He started at Tsuyama National College of Technology, Japan as a research associate on 1998. Then, he joined Okayama University of Science as a lecturer from 2005. He received Young Scientists' Prize from Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan. His research interests include mechatronics and robotics; especially wearable control systems using microcomputers and wearable control devices such as flexible pneumatic actuator, soft sensor and wearable control valve.

Shujiro Dohta is currently a professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He is also currently a Vice-president of Okayama University of Science.

He joined Okayama University of Science as a research associate on 1974. Then, he became an Exchange Faculty of Wright State University, U.S.A. from 1984 to 1985. He received his doctor degree in Engineering from Kobe University in 1990. His major in mechatronics is focusing on the development of robotics, wearable devices for rehabilitation purpose. Prof. Shujiro Dohta is currently a member of The Japan Society of Mechanical Engineers (JSME), The Society of Instrument and Control Engineers (SICE), The Robotics Society of Japan (RSJ), and The Japan Fluid Power System Society (JFPS).

Naoki Kato, master student, studies in Okayama University of Science since 2016. His research topics are focused on development of wearable rehabilitation device using soft pneumatic actuator.