IMPROVEMENT OF THE MAINTAINABILITY OF LOW-COST GAS/LIQUID SERVO VALVE

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Abstract. Recently, wearable driving systems for work assistance and rehabilitation, such as power assist suit, have received much attentions and those researches have been done actively. In this study, we aim to develop a low-cost home rehabilitation device. In the device, the size and cost of the control valve become serious concerns. In the previous study, a low-cost servo valve that was able to control the flow rate by changing the bending angle of the buckled tube was proposed and tested. In this paper, the valve is applied to the position control of rubber artificial muscle using both air and water. In addition, to apply it for a practical use, a durability test of the valve is carried out. As a result, to improve its maintainability, the valve whose buckled tubes can be easily replaced is proposed and tested.

Keywords: Servo valve using buckled tubes, Gas/liquid control valve, Maintainability

INTRODUCTION

Recently, wearable driving systems have received much attentions and those researches have been done actively [1-4]. In this study, we aim to develop a low-cost home rehabilitation device that user can buy it without official financial assistance. In a pneumatic drive wearable rehabilitation device, the size and cost of a control valve become serious concerns. Usually, the most expensive equipment in the pneumatic driving system is a control valve. In particular, an industrial 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. Its mechanism causes to be expensive. Therefore, the miniaturization and fabrication of 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]. In the previous study, a low-cost servo valve that was able to control the flow rate by changing the bending angle of the buckled tube was proposed and tested [11-13]. The valve can control the flow rate of both gas and liquid. In this paper, the valve is applied to the position control of rubber artificial muscle using both air and water. In addition, it is necessary to investigate the durability of the valve. Therefore, the durability test of buckled tube in the tested valve is also carried out. Based on the result of durability test of buckled tube, to apply it for a practical use, the valve with less maintenance whose buckled tubes can be easily replaced is also discussed.

LOW-COST GAS/LIQUID SERVO VALVE USING BUCKLED TUBES

Figure 1 shows the construction of the low-cost gas/liquid servo valve using buckled tubes developed in our previous study [14]. The valve consists of two buckled soft polyurethane tubes (SMC Co. Ltd., TUS0425) with the inner diameter of 2.5 mm and the outer diameter of 4.0 mm, a small-sized RC servo motor (GWS Co. Ltd., PICO/STD/F) with maximum speed of 500 deg./s, and an acrylic flow passage with buckled tube holder. The acrylic flow passage is connected with both buckled tubes for supply and exhaust. The passage has an output port. The passage is set on a rotational disk. By this method, the valve can drive in small area and can have fixed supply, exhaust and output ports. Each end of the supply and exhaust ports is fixed at the tube holder. The symmetrical arrangement of two buckled tubes helps to decrease the reaction torque for the motor. The operating principle of the tested valve is as follows. In the neutral position of the RC servo motor as shown in Fig.1 on the left, the sectional area of both buckled tubes for supply and exhaust at the buckled point are zero, that is, both tube are closed. When the servo motor rotates counter-clockwise, the bending angle of exhaust buckled tube is decreased and at the same time the bending angle of supply buckled tube is increased. In the condition, the buckled supply tube has a certain sectional area and the exhaust tube is closed completely. The sectional area of supply tube is increased according to counter clockwise rotational angle of the RC servo motor. When the motor rotates clockwise, the sectional area of supply port is decreased, and the sectional area of

exhaust port is increased. By this method, the valve can control both of supply and exhaust flow rate by changing rotational angle of the motor. The estimated cost of the valve is extremely low, that is about 10 US dollars. The mass of the tested valve is 31.5 g. The valve size is 55 mm in length, 53 mm in width and 38 mm in height. The valve can control the flow rate of both gas and liquid because of its simple changing mechanism of sectional area with no mechanical sliding parts.

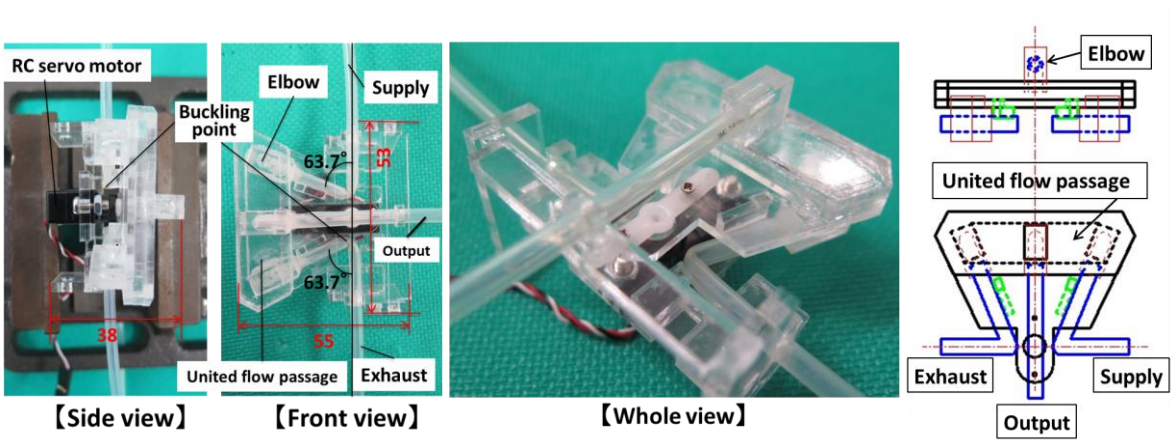


FIGURE 1. Construction of the low-cost gas/liquid servo valve using buckled tubes

Figure 2 shows the relation between the motor rotational angle and output flow rate of the tested valve. In the experiment, air supply pressure of 500 kPa is applied through a pneumatic regulator from an air compressor. From Fig. 2, it can be seen that there is an overlapped zone of plus or minus 2 degrees and the relation is almost linear. The maximum flow rate of the improved valve is 70 litter/min.

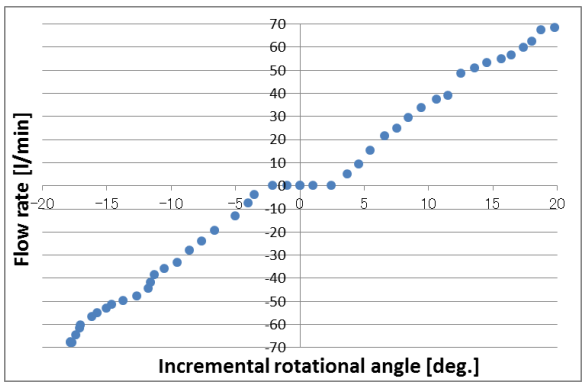


FIGURE 2. Relation between the motor rotational angle and output flow rate (air)

Figure 3 shows the transient view of the flow control using tap water. In the experiment, the supply port of the valve is connected to tap water connector. The output flow rate of tap water is changed from the maximum to zero and from zero to maximum. From Fig. 3, it can be seen that the tested valve can control the liquid flow in the same manner as the gas flow. We can confirm that the valve has an ability to apply various fields such as a medical treatment, food productions and water hydraulic systems while keeping the production cost low by simple structure of the valve. In addition, the working fluid in the valve can be isolated from outside and medical dirty objects such as a virus. Therefore, the valve can be used as a liquid medicine valve. The valve can also control the flow rate of body liquid such as a blood that includes blood red cell, fat, protein and so on.

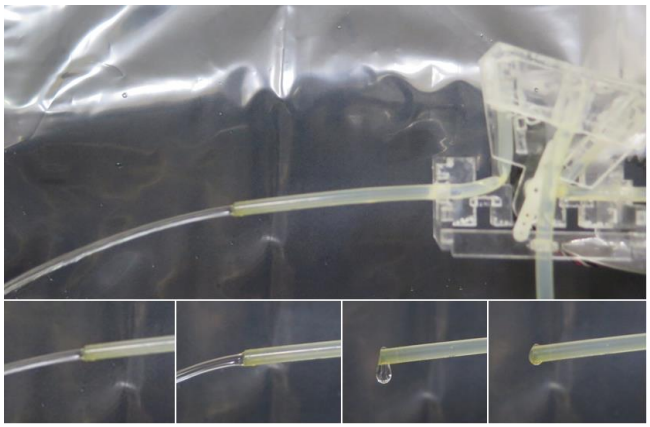


FIGURE 3. Transient view of flow rate control of tap water using the valve

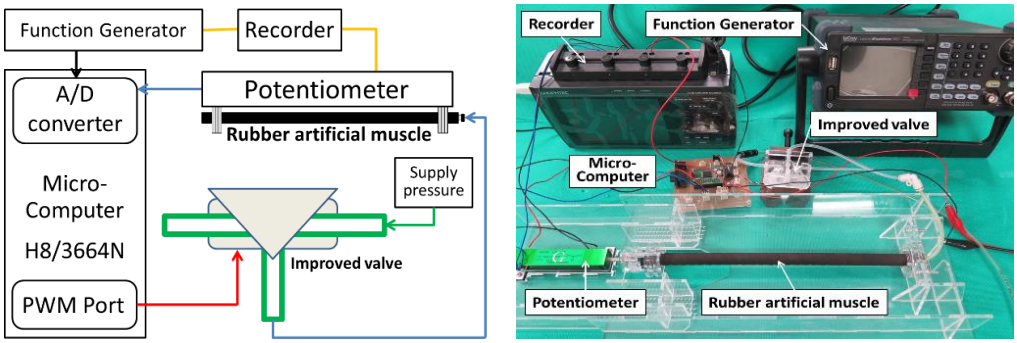
POSITION CONTROL OF ARTIFICAL MUSCLE USING AIR AND WATER

In order to confirm the validity of the tested valve, a position control of a rubber artificial muscle using the tested valve is carried out. Figures 4 (a) and (b) show a schematic diagram and a view of a position control system using the tested valve, respectively. The system consists of the tested valve, a rubber artificial muscle (FESTO Co. Ltd., MXAM-10-AA), a potentiometer (Midori Precisions Co. Ltd., LP-50F), a function generator (Teledyne LeCroy Japan Co. Ltd., wave station 2012) for desired position and a micro-computer (Renesas Co. Ltd., H8/3664F). The artificial muscle has a length of 254 mm, a stroke of 63 mm at an air supply pressure of 500 kPa and an inner diameter of 10 mm at an initial condition. The original length of artificial muscle in the case using tap water is 200 mm. The position control is done as follows. The micro-computer gets the output voltages from the potentiometer and the function generator through 10 bit A/D converter as measured and desired values. The micro-computer calculates the deviation from the desired value. It also calculates an input duty ratio for the RC servo motor in the tested valve based on a control scheme and performs the position control of rubber artificial muscle by controlling the valve. As a control scheme, a following simple PD control scheme is used.

$$u(i) = K_P e(i) + K_D (e(i) - e(i-1)), \tag{1}$$

$$d(i) = u(i) + 7.0275, \tag{2}$$

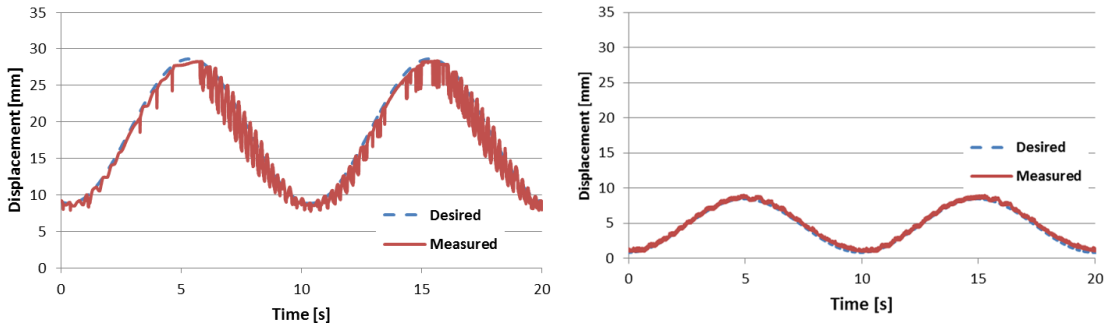
where, $e(i)$ is the deviation of the displacement from the desired position, $u(i)$ is the calculated differential duty ratio as a control input. In the case using air, the controlled parameters K_P = 0.0213 [%/mm] and K_D = 0.00053 [%/mm] are used as a proportional and derivative gains, respectively. In the case using tap water, the proportional gain K_P = 0.0333 [%/mm] and derivative gain K_D = 0 [%/mm] are used, that is P control scheme. In the control, the reference and controlled displacement are monitored by a recorder as analog voltage through the function generator and the potentiometer, respectively.



(a) Schematic diagram of the system (b) View of the system

FIGURE 4. Position control system using low-cost servo valve using buckled tubes

Figures 5 (a) and (b) show the results of tracking position control of the rubber artificial muscle using air and tap water, respectively. In the experiment, the frequency of target position is 0.1 Hz. In both cases, the desired position is set so that the muscle can move within the range of about 80% of full stroke. In Fig. 5 (b), the displacement is smaller than the case using air. This is because that the maximum supply pressure of tap water (260 kPa) used in the experiment is lower than that of air (500 kPa). It can be seen that the muscle can trace the target position in both cases. Compared with the case using tap water, the osculation around desired position can be observed in case using air even if the PD control scheme is applied. This is because output flow rate from the valve using air is larger than the case using tap water. As a result, we confirmed that the tested valve can be applied to the control system using gas/liquid as a working fluid.

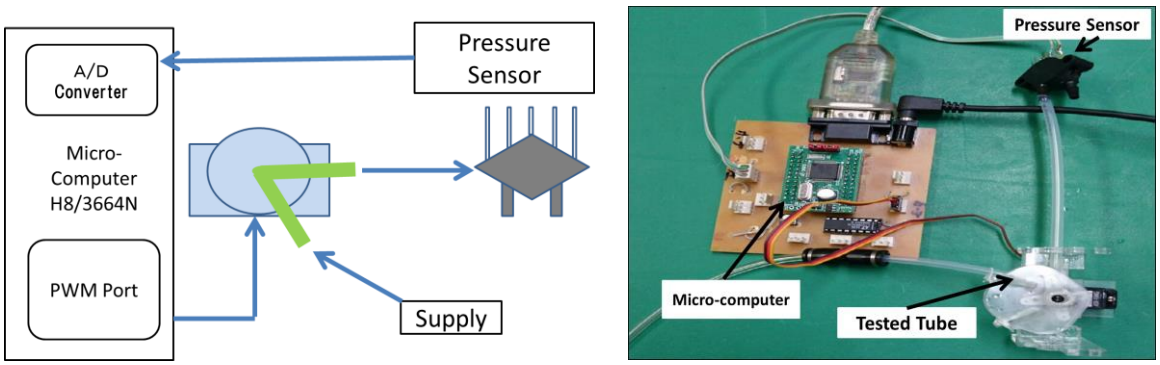


(a) Case using pressurized air (b) Case using tap water

FIGURE 5. Transient response of the rubber artificial muscle

DURABILITY TEST OF BUCKLED TUBE

The durability of the tested valve depends on the durability of the buckled tube in the valve. Therefore, a durability test of the buckled tube is carried out. Figures 6 (a) and (b) show the schematic diagram and the view of the driving system of the buckled tube for durability test, respectively. The system consists of the buckled soft polyurethane tube (SMC Co. Ltd., TUS0425) connected to the rotational disk on the RC servo motor, a pressure sensor (NXP Semiconductors Ltd., MPX5700DP), and a micro-computer (Renesas Co. Ltd., H8/3664F). The durability test is done as follows. The buckled tube is set on the rotational disk on the RC servo motor. In the initial position of the motor, the valve is closed completely. From this condition, the motor is driven to rotate 60 degrees to open the valve. The supplied pressure of 500 kPa is applied to one end of the buckled tube. The other end of the buckled tube is connected to the pressure sensor to confirm air leakage from the tube by measuring the pressure change in the tube. This process mentioned above is repeated every 0.5 seconds. In the case using normal tube with no damage, the pressure sensor detects same pressure of supplied pressure (500 kPa). In this case, the micro-computer counts the number of repetition as a successful case. If the leakage from the tube is occurred, the sensor detects lower pressure than supplied pressure of 500 kPa. In this case, the micro-computer automatically stops the motor. The micro-computer also indicates the number of successful repeating times to a monitor on PC through a serial communication unit.



(a) Schematic diagram of system (b) View of system

FIGURE 6. Driving system of bucked tube for durability test

Table 1 shows the result of durability test of buckled tube. The durability test is carried out 6 times. From Table 1, it can be seen that the maximum number of successful repeating times is 104,089 times, the minimum is 15,023 times. Figure 7 shows the view of the typical damaged tube after the durability test. We find that the split is occurred near the buckled point in most cases. Although we have not observed any problem even if the valve is used for more than one year, the result of repetition test shows that the life time of the buckled tubes is not so long. We think that the continuous driving of the valve causes the serious damage for the buckled tube because of the generated heat of deformation. However, the result of durability test also shows that it is necessary to replace the buckled tube in the valve for long time driving. Therefore, it is necessary to improve the valve so that the tube can be easily replaced.

TABLE 1. Result of durability test of the buckled tubes

Experiment	Successful repeating times	Leakage point
1st	15,023	Buckled point
2nd	58,482	Buckled point
3rd	66,098	Buckled point
4th	19,299	Buckled point
5th	104,089	Buckled point
6th	99,813	Buckled point

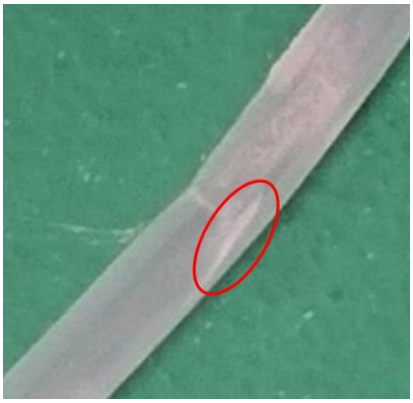
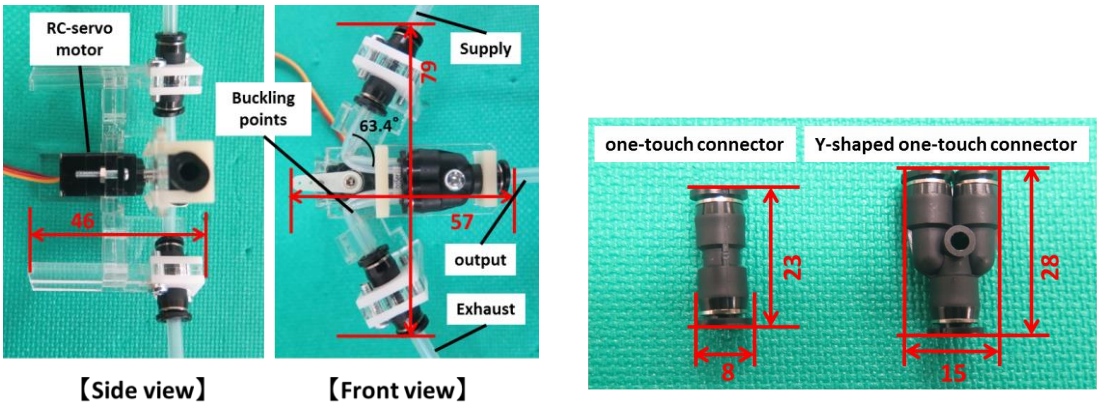


FIGURE 7. View of the damaged tube after durability test

IMPROVED VALVE WITH GOOD MAINTAINABILITY

As mentioned above, the durability of the valve depends on the durability of the buckled tubes. Therefore, it is desired that the buckled tubes can be easily replaced. However, it is not easy to replace the tubes in the tested valve as shown in Fig. 1, because the tubes are fixed to the acrylic flow passage to keep the bending condition of the tubes. Therefore, we try to improve the maintainability of the valve to be able to replace the buckled tubes easily. In addition, to improve life time of the RC servo motor in the valve and dynamics of the valve, it is necessary to decrease rotational inertia of the valve. Figures 8 (a) and (b) show the construction of the improved valve and the view of the one-touch connector to hold the buckled tubes, respectively. The improved valve consists of two buckled soft polyurethane tubes (SMC Co. Ltd., TUS0425), two one-touch connecters (Koganei Co. Ltd., US4M), a Y-shaped one-touch connecter (Koganei Co. Ltd., UY4M), a small-sized RC servo motor (Asakusa Giken Inc., ASV-15) with maximum speed of 480 deg./s, and an acrylic connecter holder. The operating principle is same as the previous valve. Compared with the previous valve, it uses one-touch connectors to hold the buckled tubes. The Y-shaped one-touch connector is used as a rotational output port and is connected to both buckled tubes for supply and exhaust. By using this method, the tubes can be easily changed and weight reduction of the rotational parts in the valve can be realized. The total mass of the improved valve is 39 g. The size of the improved valve is 57 mm in length, 79 mm in width and 46 mm in height. Compared with the previous valve, the size and mass increase, but the mass of the moving port can be reduced to 90% of the previous one.



(a) Construction of the improved vale (b) One-touch tube connectors

FIGURE 8. Improved servo valve using buckled tubes

Figure 9 shows the relation between the output flow rate and motor rotational angle of the improved valve. In the experiment, the air supply pressure of 500 kPa is applied. The tubes length of 50 and 52 mm with the same buckled point of 14 mm from the tube end are used. In Fig. 9, the blue triangles and red squares show the results using the improved valves with different buckled tubes length, respectively. The black circles show the results using the previous valve. It can be seen that the previous and the improved valves have similar characteristics. It can also be found that the overlapped zone and the gain from the motor rotational angle to output flow rate can be changed by adjusting the length of the buckled tube. However, the maximum flow rate of the valve is less than that using the previous one. It is because the overlapped zone in the improved valve is larger than that of the previous valve. Therefore, it is necessary to investigate the characteristics of the valve using various lengths and buckling points of the buckled tubes as future work. Figure 10 shows the transient view of the flow control using tap water at the improved valve. From Fig. 10, it can be seen that the improved valve can control the tap water the same as previous valve.

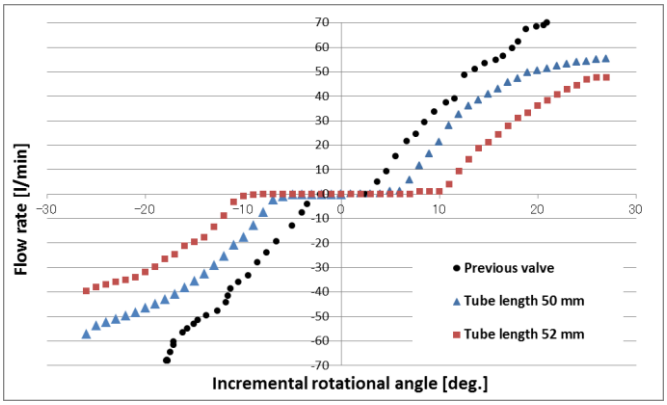


FIGURE 9. Relation between the output flow rate and motor rotational angle of the improved valve (air)

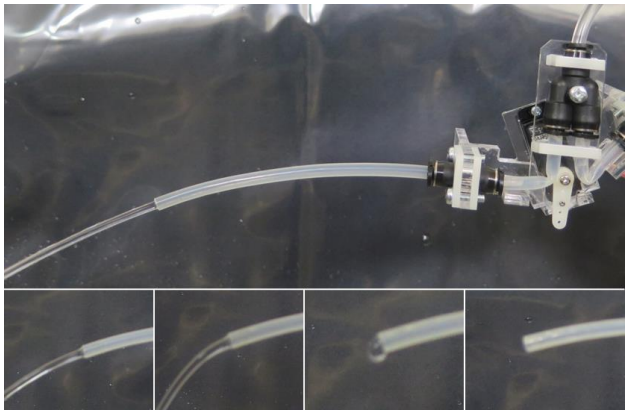


FIGURE 10. Transient view of flow rate control of tap water using the improved valve

CONCLUSIONS

This study that we aim to develop the low-cost servo valve with good maintainability can be summarized as follows. The low-cost gas/liquid servo valve using buckled tubes was proposed and tested. In order to confirm the validity of the proposed valve, the position control of the rubber artificial muscle using air/water was also carried out. As a result, it was confirmed that the tested valve can be used for control using both gas/liquid. In addition, the durability test of the buckled tube was carried out. As a result, it can be found that the buckled tube has an ability to drive it more than 15,000 times under the critical condition of continuous driving with faster movement. We also recognize the necessity for periodical replace of the buckled tubes. Based on the result of the durability test of the buckled tube, the valve with good maintainability that we can easily replace the buckled tubes was proposed and tested. The static characteristics of the valve was investigated. As a result, we found that the static characteristics of the valve can be easily adjusted by changing the length and the buckled point of the buckled tube. As future work, we are going to investigate the characteristics using various length and initial angle of buckled tubes for an optimal design.

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REFERENCES

1. ISHII, M., YAMAMOTO, K. and HYODO, K., Stand-Alone Wearable Power Assist Suit -Development and Availability-, Journal of Robotics and Mechatronics, Vol.17, 2005, pp.575-583.
2. NORITSUGU, T., TAKAIWA, M. and SASAKI, D., Development of Power Assist Wear Using Pneumatic Rubber Artificial Muscles, Journal of Robotics and Mechatronics, Vol.21, 2009, pp.607-613.
3. KOBAYASHI, H., SHIBAN, T. and ISHIDA, Y., Realization of all 7 motions for the upper limb by a muscle suit, Journal of Robotics and Mechatronics, Vol.16, 2004, pp.504-512.
4. Nagata, Y. ed., Soft Actuators -Forefront of Development-, Tokyo: NTS Ltd., 2004, pp.291-335.
5. ZHAO, F., DOHTA, S., and AKAGI, T., Development and Analysis of Small-Sized Quasi-Servo Valve for Flexible Bending Actuator, Transactions of JSME, Series C, Vol.76, No.772, 2010, pp.3665-3671.
6. UEHARA, S. and HIRAI, S., Unconstrained Vibrational Pneumatic Valves for Miniaturized Proportional Control Devices, Proceedings of 9th International Conference on Mechatronics Technology, 2005.
7. JING, S., KITAGAWA, A., LUI, C. and TSUKAGOSHI, H., A Study on a Sound Operated Valve for a Wearable Pneumatic System: 1st Report: Development of a Pilot Valve a Sound Operated Direction Control Valve, Journal of the Japan Fluid Power System Society, Vol.39, No.3, 2008, pp.54-60 (in Japanese).
8. NISHIOKA, Y., SUZUMORI, K., KANDA, T. and WAKIMOTO, S., A New Pneumatic Control System using Multiplex Pneumatic Transmission, Proceedings of 7th JFPS International Symposium on Fluid Power Toyama, 2008, pp.439-442.
9. AKAGI, T., DOHTA, S. and KATAYAMA, S., Development of Small-sized Flexible Pneumatic Valve using Vibration Motor and Its Application for Wearable Actuator, Journal of Computer Applications in Technology, Vol.39, No.1-3, 2010, pp.86-92.
10. AKAGI, T. and DOHTA, S., Development of Wearable Pneumatic Actuator and Multiport Pressure Control Valve, Journal of Robotics and Mechatronics, Vol.17, No.5, 2005, pp.529-536.
11. NASIR, A., AKAGI, T., DOHTA, S., ONO, A. and MASAGO, Y., Development of Low-Cost Wearable Servo Valve Using Buckled Tube, Applied Mechanics and Materials, Vol.393, 2013, pp.532-537.
12. NASIR, A., AKAGI, T., DOHTA, S. and ONO, A., Development of Small-sized Servo Valve Controlled by Using Buckled Tube and Its Application, Journals of the Japan Society of Mechanical Engineers, Vol.7, No.4, 2013, pp.516-527.
13. ONO, A., AKAGI, T., DOHTA, S. and NASIR, A., Improvement of Low-cost Wearable Servo Valve Using Buckled Tube, JFPS Int. Journal, Vol.8, No.2, 2015, pp.119-125.
14. HARADA, S. AKAGI, T., DOHTA, S., KOBAYASHI W., KOGA K. and NASIR, A., Compactification of Low-cost Servo Valve Using Buckled Tubes and Its Application, 2016 International Conference on Multimedia Systems and Single Processing, 2016, pp69-73.

