INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING (IJAME)
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 17, ISSUE 3, 8116 – 8127
DOI: https://doi.org/10.15282/ijame.17.3.2020.05.0609

ORIGINAL ARTICLE

Development of Reinforced Extension Type Flexible Pneumatic Actuator with Circumferential Restraints and Its Application for Rehabilitation Device

S. Shimooka[1*], T. Akagi[2], S. Dohta[2], T. Shinohara[2], Y. Hane[2] and M. Aliff[3]

[1]National Institute of Technology, Matsue College, 14-4, Nishiikuma-cho, Matsue, Shimane, 690-8518, Japan
Phone: +81-852-36-5160;
[2]Okayama university of science, 1-1, Ridai-cho, Kita-ku, Okayama, 700-0005, Japan
Phone: +81-86-256-9786; Fax: +81-86-255-3611
[3]Malaysian Institute of Industrial Technology, Universiti Kuala Lumpur, Persiaran Sinaran Ilmu, Bandar Seri Alam, 81750 Johor, Malaysia

ABSTRACT – Based on super-aging society in Japan, a welfare pneumatic device to give passive exercise for the temporally injured elderly and disabled has been actively researched and developed. In previous study, based on opinions of Physical Therapist (PT) and Occupational Therapist (OT), a home-based rehabilitation device that could give passive exercise for patients using extension type flexible pneumatic actuators (EFPA), built-in quasi-servo valves and built-in displacement sensors using a wire type linear potentiometer was proposed and tested. However, the device did not have enough force and stiffness to drive shoulders with both arms. In this study, to get enough generated force and stiffness of the device, a parallel arranged EFPA reinforced with circumferential restraint was proposed and tested. The rehabilitation device for shoulder joint using the improved actuator was also proposed and tested. The built-in attitude control system using valves, sensors and an embedded controller was also developed. As a result, it can be confirmed that the device can give passive exercise with larger moving area and enough force and torque to move patient's shoulder joint.

ARTICLE HISTORY
Revised: 27th Aug 2020
Accepted: 3rd Sept 2020

KEYWORDS
Reinforced extension type flexible pneumatic actuator,
Rehabilitation device for shoulder joint,
Embedded controller,
Built-in quasi-servo valve and sensor

INTRODUCTION

Recently, the number of older people and the reduction in infant birth rates in Japan has increased. The ratio of elderly becomes more than 26 % in 2020 [1]. The ratio is expected at about 36% in 2040. Based on this issue, various wearable pneumatic devices to support nursing care and assist welfare work for elderly and disabled using soft pneumatic actuators [2] have been actively researched and developed [3-10]. K. Yamamoto developed a wearable power assist suit for nursing care using bellows-type actuators[3]. Noritsugu and Kobayshi also developed power-assisted wear using pneumatic rubber artificial muscles[4-7]. These muscles were used to increase the force for welfare workers and the elderly. On the other hands, as taking account of the quality of life for patients or elderly, a rehabilitation device that can enhance to recover their physical ability early after injury and surgery is also required. According to Japanese law, Physical Therapist (PT) and Occupational Therapist (OT) can perform rehabilitation to the patient for just 30 minutes a day. However, from the opinions of the collaborated PT and OT, most of PT and OT have recognised that the rehabilitation for 30 minutes is insufficient. Therefore, they recommend that patients execute voluntary rehabilitation and exercise at home. Some medical reports propose the necessity of voluntary rehabilitation to prevent the bedridden state, various disease and disuse syndrome [8]. Therefore, a home-based rehabilitation device that can safely give passive exercise to patients is strongly desired. Ideally, it is better that patients can release these devices immediately when they feel the danger in rehabilitation.

As researches on such a rehabilitation device, Taniguchi and Kawasaki developed a rehabilitation device for inhibiting contracture of finger joints [9,10]. Takaiwa also developed a rehabilitation device for contracture patients using pneumatic parallel manipulator [11]. However, these devices could not be easily released by patients when they feel scared. In the previous study, the portable rehabilitation device using a flexible spherical actuator that can provide passive exercise for the wrist by changing the position of holding hands was proposed and tested [12-14]. However, these devices could not give larger moving area and force for human arm and shoulder. In this study, we aim to develop a rehabilitation device that can give a passive exercise for the temporally injured patient so that the device can be safely used at home without special knowledge. As a target body part, the shoulder joint is selected, because it is not easy to execute voluntary rehabilitation by him/herself. As a home-based rehabilitation device, it is difficult to wear wearable type devices alone without assistance. It is a serious problem that they cannot take it off immediately when patients felt danger and anxiety. Therefore, we also aim to develop a compact and stationary type rehabilitation device that patients can use it by holding its moving parts. In general, a rehabilitation device is not used by one user for an extended period, that is up to 6 months. It is necessary to make the device at low-cost so that a user can easily buy it. As a concept of proposed rehabilitation device, this device is intended for home-based voluntary rehabilitation. Therefore, it is necessary to develop a not so expensive system so that the patient can buy it. The proposed device does not also need high accuracy. The standard deviation of tracking error of ±30mm is enough because the user does not feel discomfort. Therefore, the device does not require a high accuracy sensor and precision control valve. Figure 1 shows the target image of the proposed rehabilitation system. In a typical pneumatic driving system using a wearable actuator, valves and controller (personal computer) almost occupy in whole cost and mass of the system. Usually, a valve is the most expensive equipment in a pneumatic driving system. In the previous study, various small-sized quasi-servo valves using low-cost on/off valves and control system using tiny embedded controllers have been developed [15-17]. In addition, after therapy, it needs much labour cost to wash the device in order to reuse it to keep clean.

Based on the requirements mentioned above, in this study, a stationary type rehabilitation device with a relative larger moving area that can give a passive exercise for whole upper limb while holding it by both hands is decided as a target device. In addition, in order to lift the arm and shoulder, it is necessary to consider the weight of the upper limb. The weight of human arm and shoulder is about 6% of the bodyweight [18]. The mass of human upper limbs is about 12% of the bodyweight. The average weight for a 60-year old people in Japan is about 60 kg [19]. The weight of human upper limbs for patients is about 7 to 8 kg. Therefore, the required generated force to lift the upper limbs is about 72 N or more. By taking account of these requirements, the EFPA developed in the previous study [20-22] is also used in the device, because EFPA is easy to make at low-cost (about 6 US dollars per 1 m). In the previous studies, the compact rehabilitation device for shoulder joint using EFPAs was proposed and tested [20-22]. However, the stiffness and generated force of the tested device was not enough to drive shoulder joints. In this paper, a reinforced EFPA with circumferential restraints to get suitable bending stiffness and enough generated force of the device is described. The attitude control of rehabilitation device using the tested actuator based on an analytical model also described.

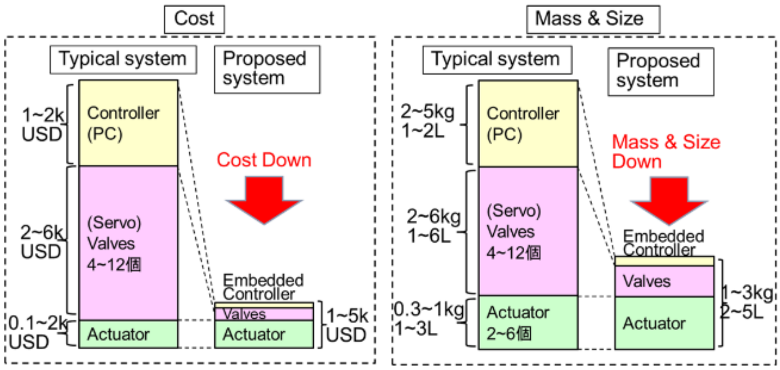


Figure 1. Image of cost and mass & size of the proposed rehabilitation device.

REQUIRED SPECIFICATION AND PREVIOUS REHABILITATION DEVICE

Figure 2 shows the construction of human shoulder joints [23]. As a basis of rehabilitation of shoulder joints, it is important to give a passive exercise for glenohumeral joint and scapula chest joint, respectively [24]. Based on the opinions of PT and OT, it is better to give a passive exercise for the scapula actively. As a voluntary training of shoulder joint, PT and OT usually recommend window cleaning exercise to patients in Japan, as shown in Figure 3. The motion leads so that scapula can move suitably. However, some patients might not carry out these motions by themselves because of the lack of force. Therefore, we aim to develop the rehabilitation device that can give a passive exercise for the shoulder joints to drive their scapula. In detail, as a target motion, the motion that the device can move hands around the circumference of a large sphere is selected. The target motion includes abduction, adduction, external and internal rotations of shoulders.

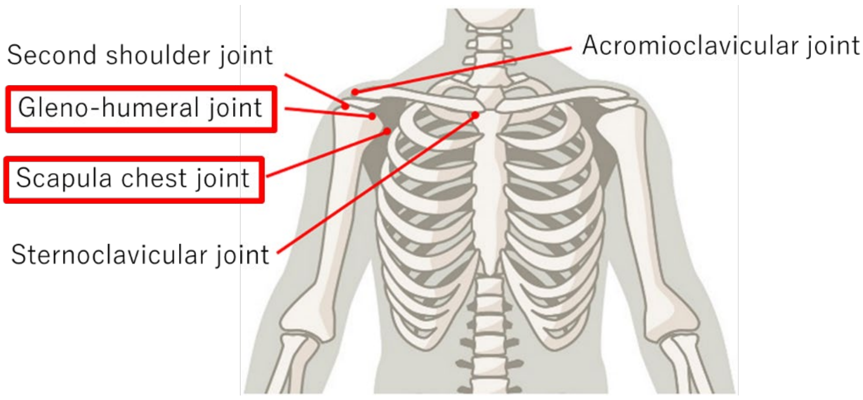


Figure 2. Construction of shoulder joint [23].

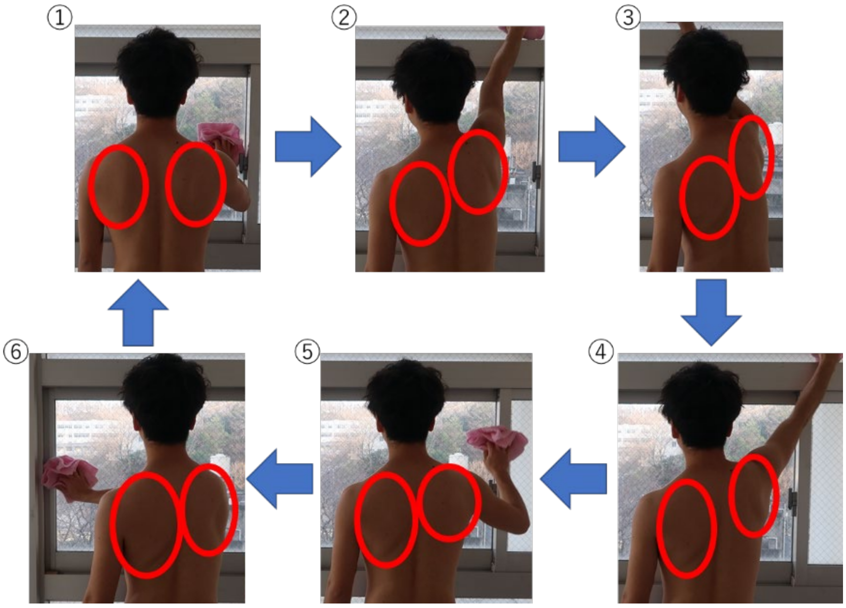
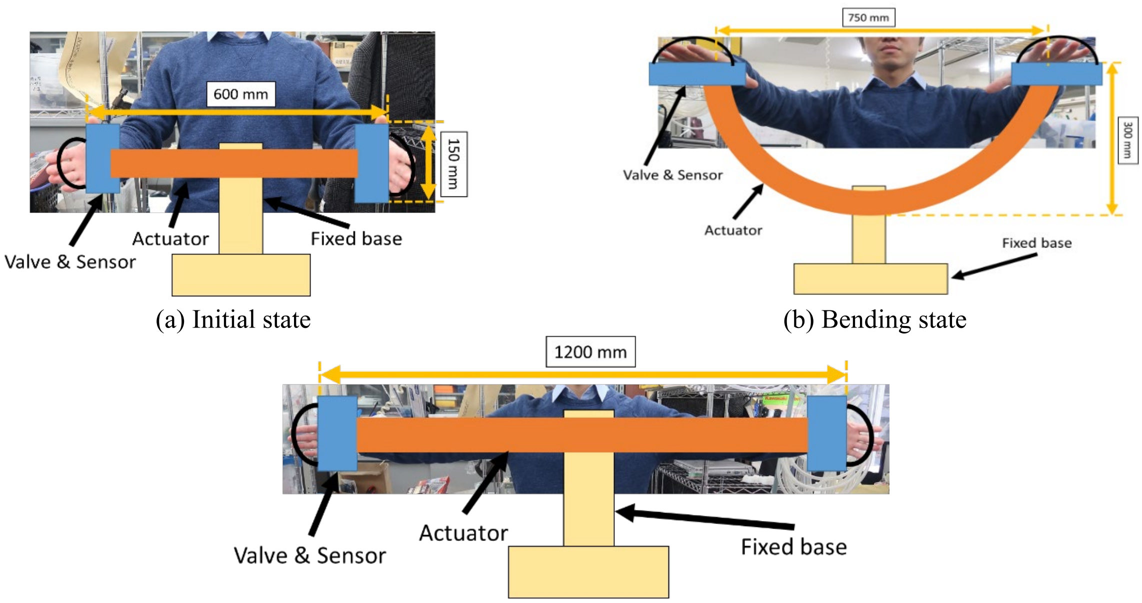


Figure 3. View of the window cleaning exercise.

Figure 4 shows the image of the rehabilitation device that was developed. As shown in Figure 4(a), the centre of the device is fixed on the table. It is also necessary to execute the bending and extending motion with compact configuration, as shown in Figure 4(b) and 4(c). In addition, by taking account of safety, it also needs that hands can be easily removed from the device whenever patients feel the danger and fear. Based on these specifications mentioned above, the rehabilitation device developed in the previous study is described in the next section as a basic device.



(a) Initial state
(b) Bending state
(c) Extending state

Figure 4. Image of the desired rehabilitation device.

Figure 5 shows the view and schematic diagram of the EFPA developed in previous studies [20,21] in order to get a larger moving area of a rehabilitation device. The actuator consists of a silicone rubber tube covered with a bellows-type nylon sleeve. The sleeve is not special equipment and is sold as an ordinal water supply hose (Swiftrans Co. Ltd., Stretching hose). Therefore, the actuator can be constructed at low-cost. The rubber tube in the sleeve has an inner diameter of 8 mm, an outer diameter of 11 mm, the original length of 200 mm, and a mass of 50 g. The material cost of the actuator is very low, that is about 5 US dollars per 1 m. The actuator can extend until about 253% of its original length when the input pressure of 500 kPa is applied. The maximum pulling force of the actuator is about 60 N. The pulling force of the actuator depends on the elastic property of the rubber tube, and it is related to the material and thickness of the rubber tube. The displacement of the actuator is inversely proportional to the thickness of the rubber tube. The pushing force of the developed actuator was not sufficient to provide a passive exercise for the shoulder joints and scapula because of lower bending stiffness. Therefore, to improve the bending stiffness of actuator, the integrated type EFPA covered by sponge was proposed and tested in the previous studies [21,22].

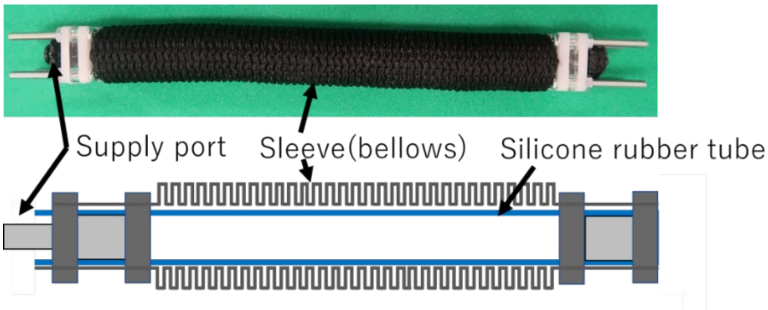


Figure 5. View and schematic diagram of EFPA [21,22].

Figure 6 shows the view and schematic diagram of a previous rehabilitation device using three integrated type EFPAs [22]. The integrated type EFPA consists of parallel arranged three EFPAs covered by the sponge. The rehabilitation device consists of three integrated type EFPAs, three-wire type linear potentiometer [14] to measure the displacement of each EFPA, three quasi-servo valves [15-16] to drive EFPAs and a micro-computer (Renesas Co. Ltd., SH7125) to control the attitude of the device. The device can be driven by only connecting a pneumatic supply tube and a power supply cable. The mass of the device is about 1.5 kg and the size is 350×185×185 mm. The maximum pushing and pulling force of the device is about 76 N and 130 N, respectively. In addition, the patients can release the proposed rehabilitation device immediately if they feel dangerous and break the device in the rehabilitation. The patient is not injured by the device because the actuator of the device is composed of flexible soft material. Therefore, the device can keep safety for patients.

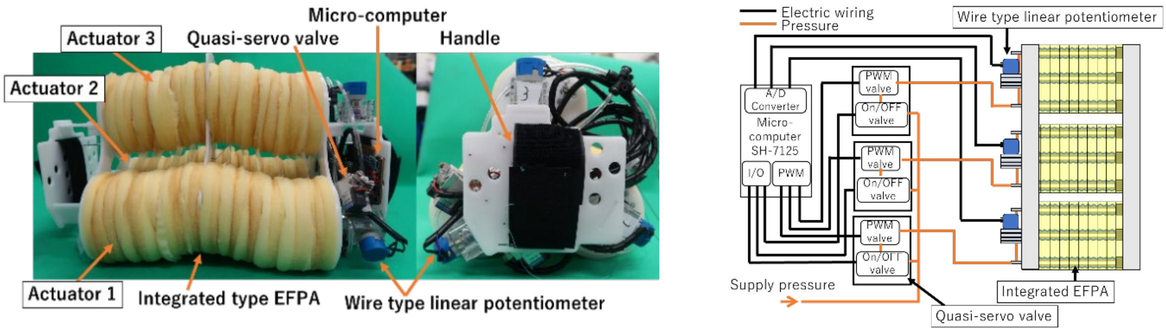


Figure 6. Previous rehabilitation device for upper limbs using improved EFPAs [22].

The attitude control of the integrated control system is carried out as follows. First, the micro-computer measures each displacement of the centre of integrated type EFPA through a wire-type linear potentiometer and A/D converter in the micro-computer. The deviation from the desired displacement is calculated by the micro-computer. The control input for each quasi-servo valve is also calculated based on the following P control scheme.

$$u_i = k_{pi} \cdot e_i \tag{1}$$

The operation of the switching valve and input duty ratio of PWM valve in each quasi-servo valve is expressed by the following equations.

Switching valve:

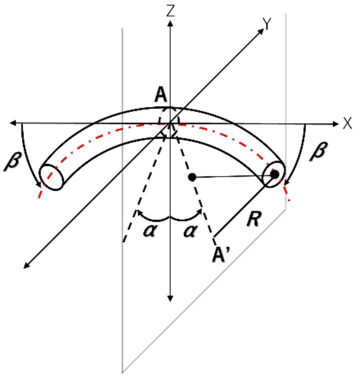
$$\begin{gathered} u_i > 0 \;\; \text{Switching valve: on (Supply)} \\ u_i < 0 \;\; \text{Switching valve: off (Exhaust)} \\ u_i = 0 \;\; \text{Switching valve: hold} \end{gathered} \tag{2}$$

PWM valve:

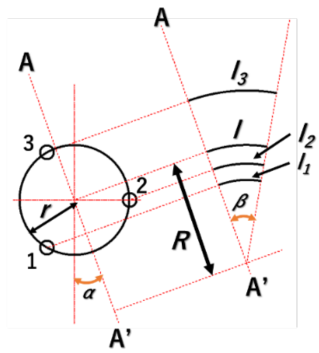
$$D_i = u_i + 47.5 \tag{3}$$

where u_i, K_{pi}, and e_i mean the input duty ratio for supply and exhaust, the proportional gain and the error between the desired and controlled displacement from the sensor, respectively. Input duty ratio D_i for each PWM valve is added 47.5 % to compensate for a dead zone of the valve output flow rate [15].

To realise to track the desired orbit so as to move hands around the circumference of a large sphere, an analytical model that can calculate the desired length of each EFPA from the desired attitude of the device is required [25]. Figure 7(a) shows the analytical model of the rehabilitation device. Figure 7(b) shows the projected drawing of each actuator from the fixed middle plate as a definition of the length of each actuator. As shown in Figure 7(a) and 7(b), the centre of a fixed middle plate of the device is defined as the origin. The integrated type EFPA located on the Z-axis is defined as actuator 3. The other actuators arranged in a counterclockwise direction from the position of actuator 3 are defined as actuator 1 and 2, respectively. l_1, l_2, and l_3 as shown in bold lines of Figure 7(b) are half lengths of each arc-shaped actuator from the fixed plate, respectively.



(a) Definition of angle α and β



(b) Definition of length of each actuator

Figure 7. An analytical model of the rehabilitation device.

By assuming that the shape of each actuator becomes circular arc while bending the device, from the geometric relationship as shown in Figure 7, the following equations can be obtained:

$$R = \frac{l}{\beta} \tag{4}$$

$$l_1 = (R - r \cdot \cos\alpha) \cdot \beta \tag{5}$$

$$l_2 = (R - r \cdot \cos(\frac{2\pi}{3} - \alpha)) \cdot \beta \tag{6}$$

$$l_3 = (R - r \cdot \cos(\frac{4\pi}{3} - \alpha)) \cdot \beta \tag{7}$$

$$L_{ri} = 2l_i \tag{8}$$

where R, l, r, α and β are the radius of curvature, the central displacement, the distance (70 mm) between the centre of each EFPA and the origin, the bending directional angle and the bending angle of the device, respectively. The attitude of the device can be decided by the bending directional angle α, the bending angle β and the central displacement l. By using Eq. (4) to (8); therefore, the desired length of each actuator L_{r1}, L_{r2} and L_{r3} can be calculated. Based on these equations, the device can be controlled.

Figure 8 shows the transient view of movement of the previous rehabilitation device based on attitude control using the analytical model. In Figure 8, both handles of the device were traced to the target trajectory. However, in the case when EFPAs was extended, the gap between sponges occurred. It is because the sponge has an ageing and creep phenomenon. Therefore, while the actuator was extended, the bending stiffness of the device is low. It causes the shoulder joints and scapula can not be lifted by the device. In order to get suitable bending stiffness and larger pushing force, we aim to develop a novel actuator using the material that does not easily deteriorate.

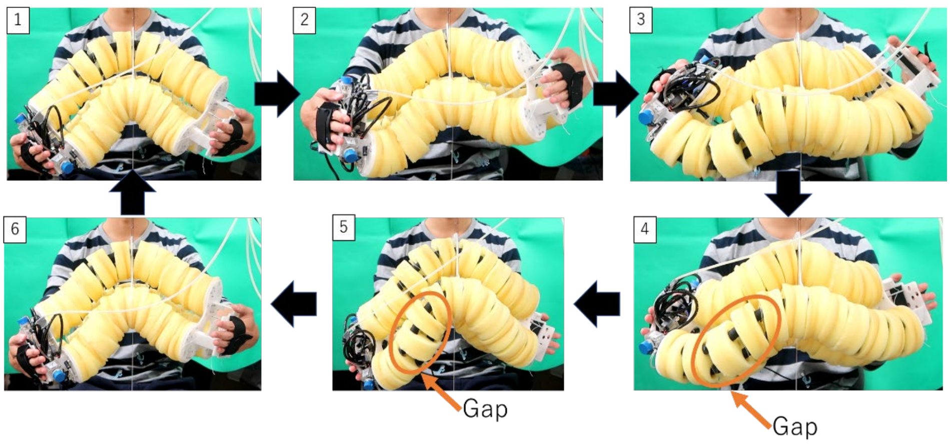
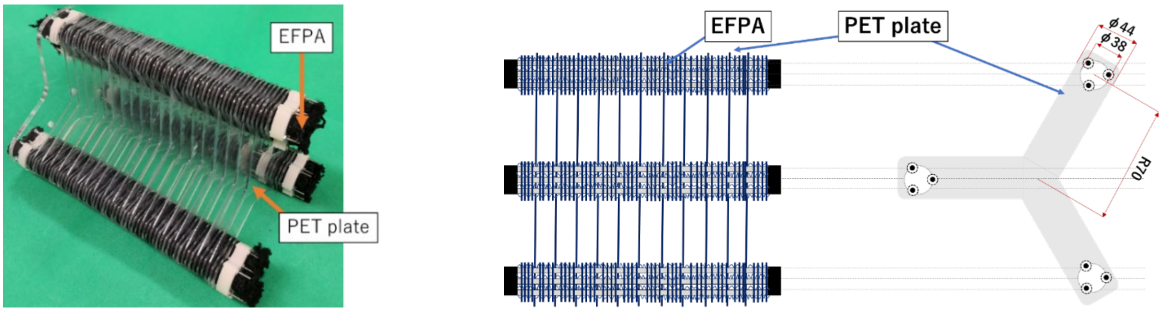


Figure 8. Transient view of the movement of the previous rehabilitation device.

REINFORCED EFPA WITH CIRCUMFERENTIAL RESTRAINTS

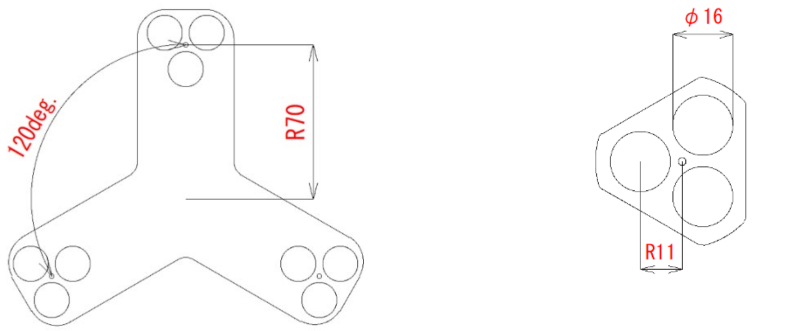
Construction of Reinforced EFPA with Circumferential Restraints

As a method to enhance the stiffness of EFPA, parallel arranged three EFPAs were restrained each other by using circumferential restraints. Figure 9 shows the view and schematic diagram of a reinforced EFPA with circumferential restraints. The actuator consists of three integrated EFPAs that parallel arranged three EFPAs were restrained each other by small circumferential restraint plates as shown in Figure 10(b). Each restraint plate with a thickness of 1 mm is inserted into bellows of the sleeve in EFPA, and it makes each actuator keep so as to arrange every 120° at a radius of 11 mm from the centre of the actuator. To enhance more bending stiffness of the actuator, three integrated EFPAs are used, and they are also restrained each other by Y-shaped restraint plates as shown in Figure 10(a). By restarting with small restraint plates, the natural stiffness (spring constant) of integrated EFPA can be increased. By restraining with Y-shaped restraint plates under the condition when each integrated EFPA is separated with a certain distance, the bending stiffness of the actuator can be increased. The principle of increasing stiffness is as follows. The shear stress is reinforced by constraining around the actuator. By increasing the number of Y-shaped restraint plates, that is restraint interval is shorter, the stiffness of actuators becomes larger.



(a) (b)

Figure 9. (a) View and, (b) schematic diagram of reinforced EFPA with circumferential restraints.



(a) Y-shaped restraint plate (b) Small restraint plate

Figure 10. Shape of restraint plates (with 1 mm thickness).

Characteristic of Reinforced EFPA with Circumferential Restraints

Figure 11 shows the relation between the input pressure and the generated pushing force of the reinforced EFPA. In Figure 11, each symbol shows the difference in pitch of bellows, where Y-shaped restraint is set. Pitch 2 means that Y-shaped and small restraint plates are set in bellows alternately. In the experiment, the reinforced EFPA was connected to the force sensor in series. The input pressure was increased every 50 kPa until the buckling of the actuator occurs. From the pressure when the buckling occurs, input pressure was decreased every 50 kPa until 0 kPa. In this condition, the generated pushing force of the actuator was measured. As a result, it can be seen that the generated pushing force of the actuator is increased according to the use of a smaller pitch. From the result, the pushing force of the actuator with pitch 2 and 3 are almost the same. It is also found that the pushing force of actuator with pitch 6 is larger than the case using pitch 5. The difference of pushing force between the actuator with pitch 4 and 6 is not found. Overall, it can be said that there is no clear rule between the pushing force and pitches. However, it seems that actuators with pitch 5 and 6 are easily buckled when a larger input pressure is applied. The maximum generated pushing force of about 180 N can be obtained. The pushing force of the tested actuator can be improved than the case using the previous sponge type integrated EFPA that is about 76N. It can be concluded that this value of the pushing force is enough to lift human arms because the required generated force to lift the upper limbs is about 72 N.

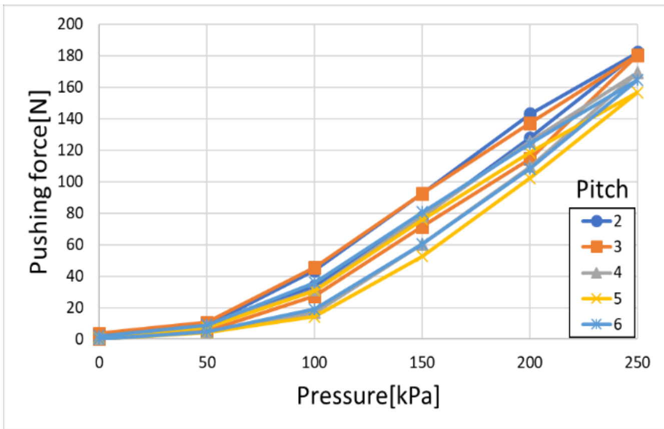


Figure 11. Relation between input pressure and pushing force of the reinforced EFPA.

Figure 12 shows the relation between the input pressure and the generated pulling force of the reinforced EFPA. In the experiment, since the generated pulling force of the actuator depends on elastic rubber tubes in EFPA in principle, the reinforced EFPAs with pitch 2 and 4 were used to measure it. At the beginning of the measurement, the force sensor was connected to EFPA in series under the condition when a supply pressure of 500 kPa was applied (as saturated pressure). In this condition, the generated pulling force of the actuator was measured by decreasing input pressure every 50 kPa. As a result, the maximum generated pulling force is about 420 N. By taking account that the generated pulling force of single EFPA is about 60 N, the generated pulling force of the reinforced EFPA is less than the theoretical pulling force (of about 540 N). It seems that it caused by the frictional force between the restricted sleeve and the inner rubber tube.

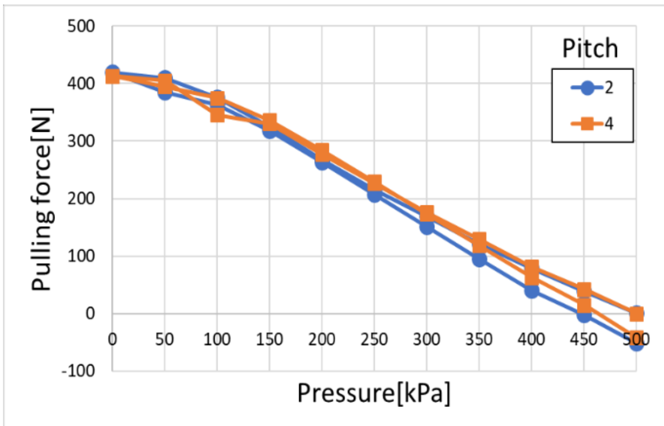
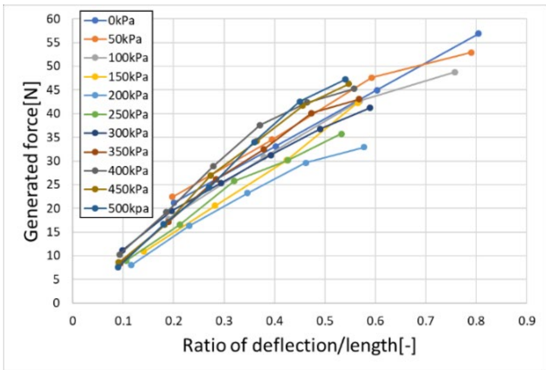
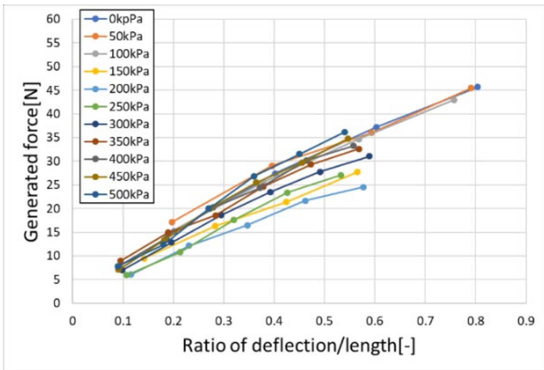


Figure 12. Relation between input pressure and pulling force of the reinforced EFPA.

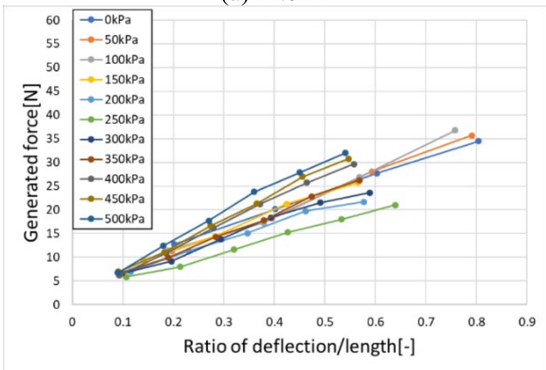
Figures 13(a) to 13(e) show the bending stiffness characteristics of the reinforced EFPA. Figure 14 shows an overview of the experimental setup to measure the bending stiffness of the actuator [22]. In the experiment, the vertical pulling force acted at the top end of the actuator was measured under the condition when the actuator was extended with various supply pressure, as shown in Figure 14. Therefore, when the supply pressure is low (0 to 100 kPa), as the length of the actuator is short, the ratio of deflection/length becomes high (0.5 to 0.8) as shown in Figure 14. When the length of the actuator is long by giving higher supply pressure, the ratio of deflection/length becomes small. Each figure shows the result using each pitch. In each figure, each colour means the difference of input pressure. The inclination in the graph means the bending stiffness of the actuator. As a result, it can be seen that the bending stiffness of the actuator is almost the same even if input pressure is changed. From Figure 13(a) to 13(c), it can also be seen that the stiffness of the actuator becomes larger as the increasing number of Y-shaped restraint plates. This value of stiffness is saturated by using a pitch of more than 4. It is also found that the bending stiffness of reinforced EFPA has almost constant between 40.7 and 53.1 N/(-). This value is more stable and larger than the case using the previous EFPA, that is between 31.1 and 51.8 N/(-).



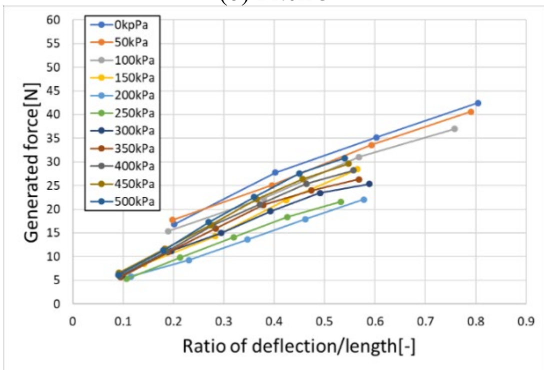
(a) Pitch 2



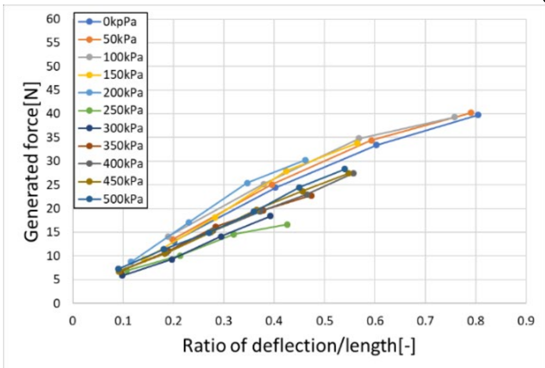
(b) Pitch 3



(c) Pitch 4



(d) Pitch 5



(e) Pitch 6

Figure 13. Bending stiffness characteristics of the reinforced EFPA.

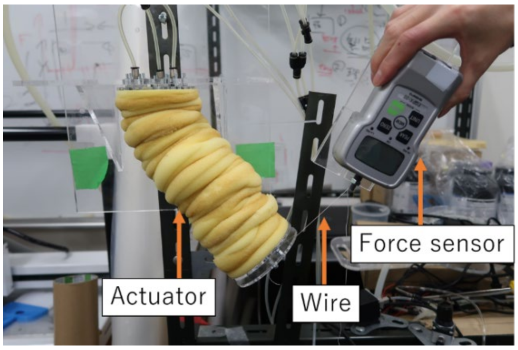


Figure 14. Overview of experimental setup to measure bending stiffness of the actuator [22].

Attitude Control of the Rehabilitation Device using Reinforced EFPA

Figure 15 and 16 show the view and schematic diagram of the improved rehabilitation device using the reinforced EFPA, respectively. From Figure13, the actuator with pitch 4 was decided to use from the trade-off between weight and stiffness of the device. For example, when the pitch 2 is used, many Y-shaped plates (of 33) are required. In the case of an actuator with pitch 4, 12 plates are needed. Therefore, the weight with larger pitch becomes lighter. In addition, in the case of pushing motion, the buckling is easily occurred by using the actuator with pitch 5 and 6. Therefore, the actuator with pitch 4 was selected as the optimal rehabilitation device. In addition, under consideration to get enough moving area to move shoulder joints and scapula, the length of the reinforced EFPA was decided 600 mm. The improved rehabilitation device consists of the large-sized reinforced EFPA, three-wire type linear potentiometers to measure the displacement of each centre of integrated EFPA, three quasi-servo valves to drive the EFPA and a micro-computer to control the device. The attitude control method is the same as the previous one, which uses Eq. (4) to (8). The centre of the device was also set on the table. The size of the tested device is about 600 × 185 ×185 mm, and the weight of the device is about 1.8 kg.

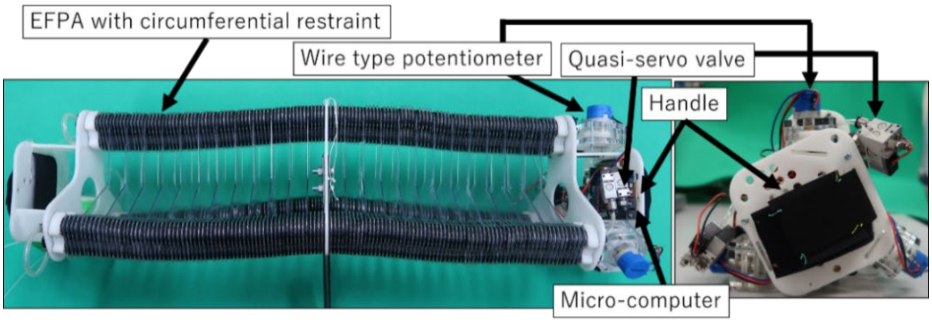


Figure 15. Rehabilitation device using large-sized reinforced EFPA.

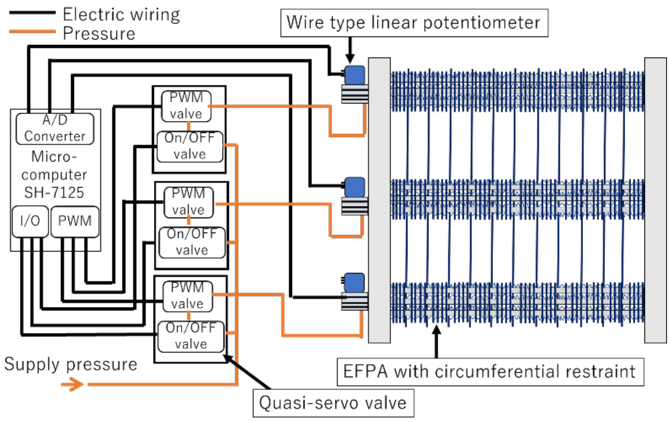
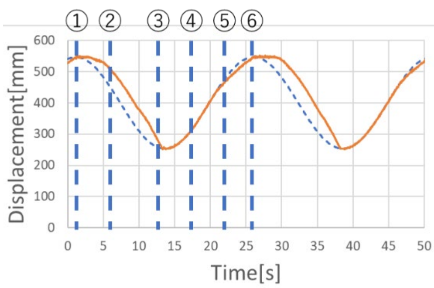
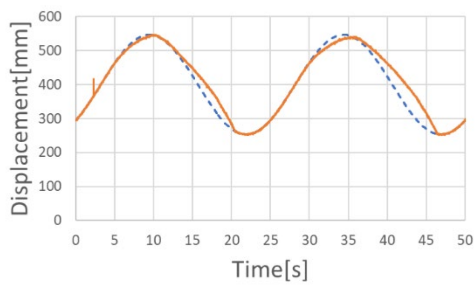


Figure 16. Schematic diagram of the improved rehabilitation device.

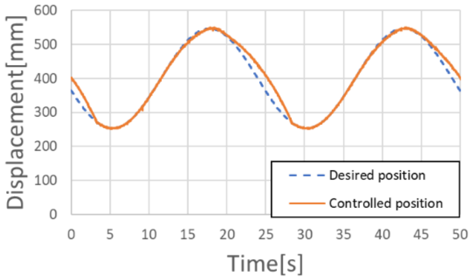
Figure 17 shows the transient response of the length of each integrated EFPA in attitude tracking control using the improved rehabilitation device. In the experiment, the supply pressure of 500 kPa was applied. As the desired orbit of each end of the device, the rotational motion with constant bending angle β of $\pi/3$ rad and the central half-length l of 400 mm was given. The bending directional angle α was periodically changed from 0 to 2π every 25 seconds. In Figure 17, the solid and broken lines show the controlled displacement obtained from potentiometers and the desired displacement of each integrated EFPA calculated by the model, respectively. From Figure 17, it can be found that the controlled displacement of each actuator can relatively well trace each desired displacement. The standard deviation of tracking displacement error is about 28 mm. Figure 18 shows the transient view of the movement in attitude control of the device. Figure 19 shows the transient view of the movement of the scapula in attitude control of the device. From Figure 18, it can be seen that the passive exercise can be given for shoulder joints of the patient without buckling the device. It can also be found that the device has suitable bending stiffness. From Figure 19, it can also be seen that the scapula can be driven frequently so that the patient can carry out window cleaning exercise that PT and OT recommend as a voluntary rehabilitation.



(a) Actuator 1



(b) Actuator 2



(c) Actuator 3

Figure 17. Transient response of length of each integrated EFPA in attitude tracking control using the improved rehabilitation device.

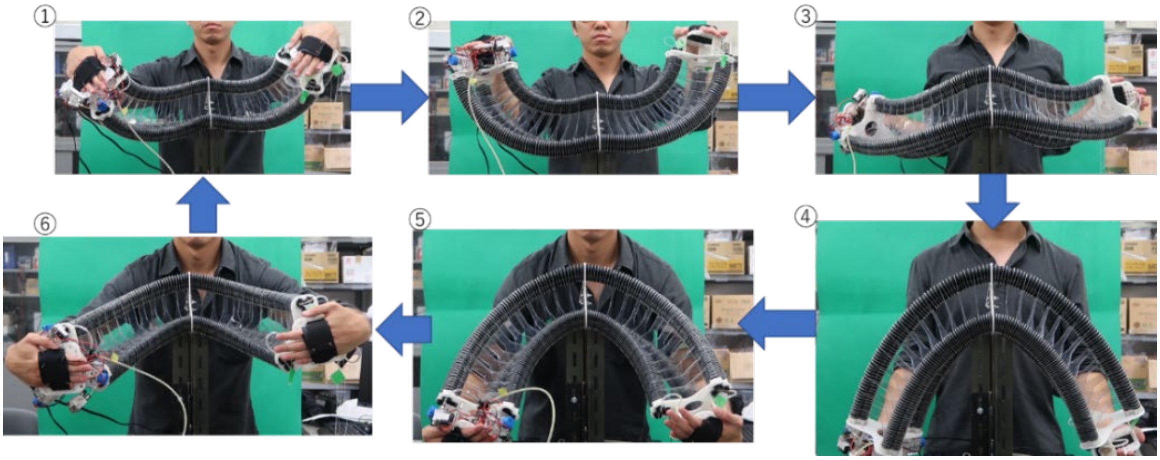


Figure 18. Transient view of device movement in attitude control.

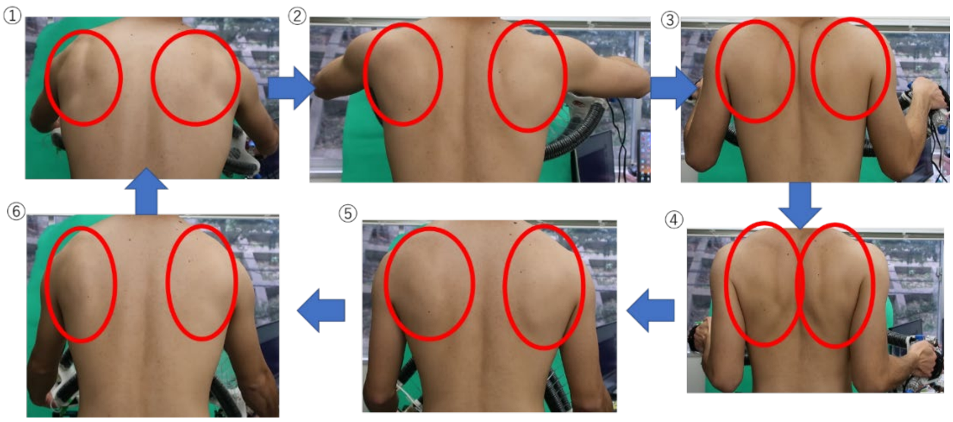


Figure 19. Transient view of scapula movement in attitude control of the device.

CONCLUSION

This study aims to develop a reinforced extension type flexible pneumatic actuator with circumferential restraints and its application for rehabilitation device. It can be summarised as follows.

i. To get suitable bending stiffness and generated force of the home-based rehabilitation device that can give passive exercise for shoulder joint, the reinforced EFPA with circumferential restraints was proposed and tested. As a result, it could be seen that the maximum pushing force of about 180 N was improved compared by using the previous one (76 N). It was also found that the bending stiffness of the actuator improved and was almost constant between 40.7 and 53.1 N/(-) even if the input pressure changed. It could be concluded that the tested reinforced EFPA had enough pushing and pulling force to drive shoulder joints with suitable bending stiffness.

ii. The rehabilitation device for shoulder joints that consists of the reinforced EFPA with the larger moving area, three-wire type linear potentiometers, quasi-servo valves and a built-in micro-computer was proposed and tested. The tracking attitude control using the proposed model was carried out. As a result, it was confirmed that the controlled displacement for each integrated EFPA in the device could trace relatively well the desired trajectory with standard deviation error of 28 mm. It can be found that passive exercise can be given for shoulder joints of the patient without buckling the device. It could also be confirmed that the scapula can be suitably driven so that the patient could execute window cleaning exercise that PT and OT recommend as a voluntary rehabilitation.

As future work, we are going to carry out the analysis of the tested device by using finite element analysis software to get the model for designing it. In addition, based on the model, we are going to develop the renewal device that has the optimal stiffness according to PT and OT evaluation.

ACKNOWLEDGEMENT

This research was supported by MEXT in Japan through a Financial Assistance Program for QOL Innovative Research (2012-2016) and a Grant-in-Aid for Scientific Research (C) (Subject 16K06202 & 19K04265).

REFERENCES

[1] Annual report on the ageing society [Summary] FY 2019, Retrieved from: https://www8.cao.go.jp/kourei/english/annualreport/-2019/pdf/2019.pdf; June 2019.

[2] Nagata Y. Soft actuators, Forefront of Development. NTS Ltd., 2004, p 291–335.

[3] Ishii M, Yamamoto K, Hyodo K. Stand-alone wearable power assist suit (development and availability). Journal of the Japan Society of Mechanical Engineers 2006; 72(715): 175–182.

[4] Noritsugu T. Pneumatic soft actuator for human assist technology. In: Proceedings of the 6th JFPS International Symposium on Fluid Power, Tsukuba, Japan, pp. 11–20; 2005.

[5] Sasaki D, Noritsugu T, Yamamoto H, Takaiwa M. Development of power assist glove using pneumatic artificial rubber muscle. Journal of the Robotics Society of Japan 2006; 24(5): 640-646.

[6] Noritsugu T, Takaiwa M, Sasaki D. Development of power assist wear using pneumatic rubber artificial muscles. Journal of Robotics and Mechatronics 2008; 21(5): 27–31.

[7] Kobayashi H, Shiban T, Ishida Y. Realisation of all 7 motions for the upper limb by a muscle suit. Journal of Robotics and Mechatronics 2004; 16(5): 504–512 .

[8] Council of Bureau of Social Welfare and Public Health Tokyo Metropolitan Government. Retrieved from: https://www.fukushihoken.metro.tokyo.lg.jp/iryo/sonota/riha_iryo/kyougi01/rehabiri24.files/siryou242.pdf; February 2013 (in Japanese).

[9] Taniguchi H, Wakimoto S, Suzumori K. Development of a hand rehabilitation system to prevent contracture for finger joints based on the therapy of occupational therapists (Massage a hand and range of motion exercises using pneumatic soft actuators). Journal of the Japan Society of Mechanical Engineers, 2014; 80(820): TRANS0348.

[10] Kawasaki H, Ito S, Ishigura Y, Nishimoto Y, Aoki T, Abe T, Sakaeda H, Ojika T, Mouri T, Ueki S. Hand rehabilitation assist robot designed with assistance for thumb opposability. Journal of the Japan Society of Mechanical Engineers 2008; 74(748): 3019-3027.

[11] Takaiwa M, Noritsugu T, Sasaki D. Wrist rehabilitation using pneumatic parallel manipulator ~ Proposal of rehabilitation based on EMG signal. Transactions of the Japan Fluid Power System Society 2012; 43(3): 85-91.

[12] Matsui Y, Akagi T, Dohta S, Aliff M, Liu C. Development of portable rehabilitation device using flexible spherical actuator and embedded controller. Lecture Notes in Electrical Engineering 2014; 293(1): 231-238.

[13] Matsui Y, Akagi T, Dohta S. Development and control of flexible spherical actuator for portable rehabilitation device. International Journal of Materials Science and Engineering 2015; 3(1): 49-54.

[14] Matsui Y, Akagi T, Dohta S, Kobayashi W, Tamaki H. Development of flexible spherical actuator with 3D coordinate measuring device. Journal of Flow Control Measurement & Visualization 2018; 6(2): 95–106.

[15] Zhao F, Dohta S, Akagi T. Development and analysis of small-sized quasi-servo valve for flexible bending actuator. Transactions of the Japan Society of Mechanical Engineers Series C 2010; 76(772): 3665-3671.

[16] Shimooka S, Dohta S, Akagi T, Moriwake Y, Zhao F. Estimation of pressure control performance in low-cost quasi-servo valve using embedded controller. Lecture Notes in Electrical Engineering 2014; 293(1): 359–366.

[17] Shimooka S, Dohta S, Akagi T, Moriwake Y. Analysis and simulation of small-sized quasi-servo valve using tiny on/off control valve. Lecture Notes in Electrical Engineering 2015; 345(1): 59–66.

[18] Ogawa K. Evidence-based nursing ergonomics and body-mechanics. Tokyo Denki University Press., 2008, p. 28. (in Japanese)

[19] Health Japan 21 (the second term) Analysis and assessment project. Retrieved from: https://www.nibiohn.go.jp/eiken/kenkounippon21/eiyouchousa/keinen_henka_shintai.html; 2018 (in Japanese), November 2018.

[20] Shimooka S, Dohta S, Akagi T, Kobayashi W, Yoneda M. Development of portable rehabilitation device using flexible extension type soft actuator with built-in small-sized quasi servo valve and displacement sensor. JFPS International Journal of Fluid Power System 2018; 11(2): 18-25.

[21] Suzuki Y, Akagi T, Dohta S, Kobayashi W, Tamaki H, Matsui Y, Shimooka S. Development of tetrahedral type rehabilitation device using flexible pneumatic actuators. International Journal of Mechanical Engineering and Robotics Research 2018; 7(4): 409-414.

[22] Shimooka S, Dohta S, Akagi T, Kobayashi W, Shinohara T. Improvement of home portable rehabilitation device for upper-limbs. JFPS International Journal of Fluid Power System 2019; 12(1): 10-18.

[23] Home training for shoulder bouldering taught by physiotherapist "shoulder, scapula" (in Japanese). Retrieved from: https://machicon.jp/bouldering/column/3657, March 2019.

[24] Senda M, Katayama Y, Kaneda D. Rehabilitation in the shoulder disease. The Japanese Journal of Rehabilitation Medicine 2016; 53(12): 928-933.

[25] Aliff M, Akagi T, Dohta S. Trajectory control of robot arm using flexible pneumatic cylinders and embedded controller. In: 2015 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Busan, Korea, pp. 1120-1125; 2015.