Development of Simple Rehabilitation Device Using Flexible Linear Stepping Actuators

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***Abstract*— The progress of the aging society in Japan has deteriorated. Therefore, the rehabilitation devices and power assistive devices have been desired from the viewpoint of quality of life. In such devices, a soft actuator is useful to construct a human-friendly rehabilitation device. In addition, the soft actuator with both a longer stroke and a larger generated force is desirable for a rehabilitation device. Therefore, we have developed a various type of flexible linear stepping actuators that can push and pull the flexible tube while changing the gripping position of the tube. They can generate larger force and realize position control without sensor. In this paper, the development of simple rehabilitation device for upper limb using two flexible linear stepping actuator is described. The construction and the operating principle of the simple rehabilitation device are also described. As a result, it can be confirmed that the tested device can give a passive exercise with larger moving area for human arm**

***Index Terms*— Simple rehabilitation device, Soft actuator, backdrivability, Pneumatic flexible stepping actuator, passive exercise**

I. Introduction

The progress of Japanese aging society is an important problem from the view point of Japanese economy and welfare business [1]. Recently, Japanese government promotes to decrease the medical and welfare budget for elderly care and senior citizens. It is better that the senior can work in longer period to support Japanese economy and industry. Therefore, in order to keep and recover their physical ability after an accident such as injury, a rehabilitation device that can give passive exercise to user at home without special knowledge is required from the view point of quality of life [2-5]. To realize a home rehabilitation device, a soft pneumatic actuator is very useful. A pneumatic actuator has the tolerance based on the compressibility of air. As a research history about device using soft pneumatic actuator, K. Yamamoto developed a wearable power assisted suit using pneumatic balloon actuator for nursing care [2]. T. Noritsugu also developed a power assisted wear for nursing care using McKibben type pneumatic rubber artificial muscle that is made of silicone rubber tube covered by nylon mesh [4]. H. Kobayashi also developed a muscle suit using the muscle for factory application [5]. In such devices, it is required to use human-friendly soft actuators in order to prevent to injure the human body. As mentioned above, McKibben type rubber artificial muscle is used in various human friendly driving devices. The muscle is also well known as a soft actuator with large generated force. However, the muscle does not have a long stroke. The maximum displacement of the muscle is less than one fourth of its original length [6].

On the other hand, as a soft actuator that can move with a long stroke, the flexible pneumatic cylinder was proposed and tested in our laboratory [7]. The various rehabilitation devices using the cylinders were also proposed and tested [8,9]. However, the generated force of the cylinder is insufficient, that is only 15 N, to apply to power assistive and rehabilitation devices for whole upper limb including shoulder and arm. In addition, a flexible displacement sensor with long stroke while deforming its form according to the soft actuator's shape is difficult to be realized. It is very attractive to develop a soft actuator that can generate both larger force and longer displacement and its displacement can be controlled easily.

Based on this background, a linear flexible stepping actuators with a long stroke and a large generated force using pneumatic balloons and pneumatic driven chucks was proposed and tested in the previous study [10,11]. The tested actuator can push or pull the flexible tube while changing the gripping point of the flexible tube by using the pneumatic driven chucks. To improve the moving speed of the actuator, a linear stepping actuator using typical pneumatic cylinders was proposed and tested [12]. A flexible robot arm using three tested actuators was also successfully developed [12]. The generated force of the tested linear stepping actuator was improved so as to prevent the slip between the chuck and tube. A novel mechanical check that can hold the tube from both inner and outer sides of tubes by using cylindrical moving core with a magnet was also proposed and tested. In the next step, it is necessary to apply the tested actuator to simple rehabilitation and confirm the function of the tested device as a home rehabilitation device. In this paper, the construction and the operating principle of a tested simple rehabilitation device using two flexible linear stepping actuators are described. The

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driving test of giving passive motion to human shoulder and arm using the tested device is also carried out.

II. Previous Cylinder Type Flexible Linear Stepping Actuators

A. Construction

In the previous study [12], as a flexible pneumatic actuator that can generate larger force and work with a longer stroke, a cylinder type flexible linear stepping actuator was proposed and tested. Fig. 1 shows the construction of the tested cylinder type actuator. The actuator consists of two sets of three double acting type pneumatic cylinders and three pneumatic chuck. One set of three cylinders has a stroke of 50 mm (Koganei Co., PBDA 16x50-M). The other set consists of three cylinders with a stroke of 5 mm (Koganei Co., PBDA 16x5-M). By using two moving stages connected to cylinders with different strokes, the actuator can move every 50 mm for faster motion and realize positioning with the resolution of 5 mm by using shorter stroke cylinders. The inner cylinder diameter of 16 mm is decided so as to get the required generated force of more than 300 N when the supplied pressure of 500 kPa is applied. The ends of six cylinders are connected with a base stage with the pneumatic chuck and they are set every 60 degrees with radius of 33 mm from the center of the base stage. The rod ends of each set of three cylinders are also connected with the moving stage with the pneumatic chuck. The improved actuator has a length of 133 mm and an outer diameter of 80 mm. The mass of the actuator is 0.7 kg.

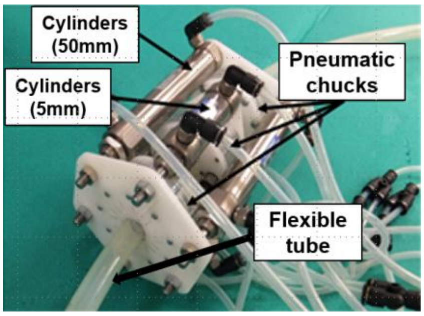


Figure 1. View of cylinder type linear flexible stepping actuator.

The cylinder type actuators also has a backdrivability while the pneumatic chuck is not driven. However, the generated force of the actuator (about 90 N) is smaller than the theoretical value of the actuator, that is 272 N. This theoretical value can be obtained by using the sectional area of cylinders and supplied pressure. It is caused by the slipping on the pneumatic chuck. Therefore, a novel pneumatic chuck was proposed and tested.

B. Magnetic Core Type Pneumatic Chuck

Fig. 2 shows the view and the schematic diagram of a magnetic core type pneumatic chuck developed in our group[13]. The chuck consists of two ring-shaped neodymium magnets, I-shaped cylindrical plastic core in the flexible tube, a doughnut-shaped diaphragm and a mechanical chuck. The doughnut-shaped diaphragm is made of rubber film with the thickness of 0.5 mm and a ring-shaped plastic plate. The diaphragm has a doughnut-shaped sectional area with an inner diameter of 24 mm and an outer diameter of 36 mm. The mechanical chuck consists of two claws located between the fixed and moving bases with a slope angle of 45 degrees from the contacted face of the diaphragm. Both sides of each claw in the chuck also have a slope so as to meet face to face. The cylindrical plastic core consists of ring-shaped plastic disks and a ring-shaped neodymium magnet. The magnet has a dimension with the outer diameter of 8.5 mm and the inner diameter of 5.5 mm. They are penetrated by a screw and a nut. In the mechanical chuck, the ring-shaped neodymium magnet with the outer diameter of 20 mm and the inner diameter of 12 mm is set on the flexible tube to attract the magnet of the moving core.

Fig. 3 shows the schematic diagram of the operation of the tested chuck. The operating principle of the chuck is as follows. By attracting both magnets of the chuck and the core each other, the core can automatically track the movement of the chuck. When the supplied pressure is applied to the diaphragm, the diaphragm pushes two claws through the round-shaped plate. The flexible tube is clamped from both inner and outer sides by claws and moving core. By this method, the chuck can hold the tube surely.

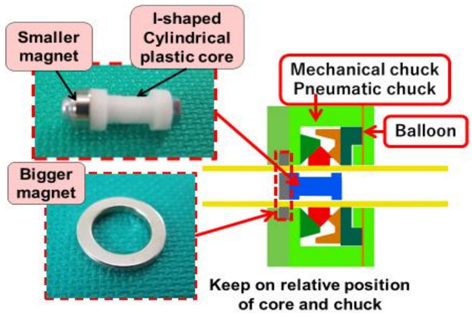


Figure 2. Schematic diagram of inner construction and view of magnetic core type chuck.

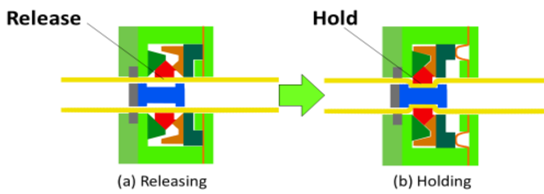


Figure 3. Operating principle of magnetic core type chuck.

C. Operating Principle of the Actuator

Fig. 4 shows the operating principle of the tested actuator. To simplify the description of the operating principle, the simplified schematic diagram of the actuator only using one set of cylinders is used. The operating principle is as follows: First, the base side chuck is driven to hold the tube as shown in Fig. 4 (1). In the condition, as shown in Fig. 4 (2), the right side chambers of cylinders are pressurized. A moving stage with the pneumatic chuck moves toward right. When the moving stage reaches at the right side stroke end, the chuck on the stage is activated to hold the tube as shown in Fig.4 (3). After that, as shown in Fig.4 (4), the chuck on the moving stage is driven and the chuck on the base stage is released. Under the condition that the chuck on the moving stage holds the flexible tube, air in the right side cylinder chamber is exhausted as shown in Fig.4 (4). At the same time, as shown in Fig.4 (5), the left side chambers of the cylinders are pressurized. While the chuck on the moving stage keeps holding the tube, the flexible tube is pushed toward left as shown in Fig.4 (6). By repeating this procedure, the tube can move toward left every certain stroke.

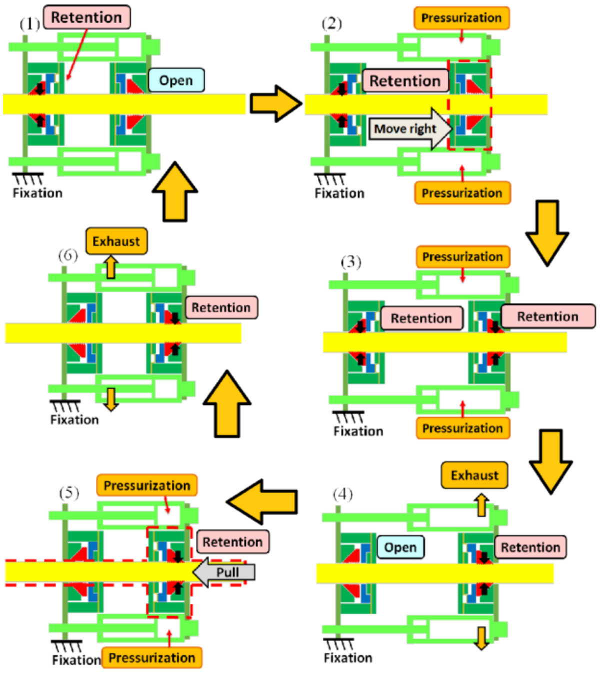


Figure 4. Operating principle of the cylinder type flexible linear stepping actuator.

As a result of measurement of generated force of the actuator, the maximum generated force of 260 N can be obtained. This value is almost same as the theoretical generated force of 272 N using three cylinders. Under consideration of the frictional force of cylinders, that is about 11 N, the measured generated force is equal to the maximum generated force of cylinders. It means that the holding force of the tested pneumatic chuck is effective as a holding device. This is because the theoretical gripping force of two claws in the chuck calculated by the sectional area of the diaphragm and the supply pressure, that is 140 N, is much small than the obtained holding force of the actuator.

III. Simple Rehabilitation Device

A. Design Concept of Rehabilitation Device for Shoulder

The tested flexible linear stepping actuator is successfully developed. In the next step, it is necessary to develop a rehabilitation device that requires larger force and moving area as an application of the tested actuator to realize a home rehabilitation device. In this study, the rehabilitation device for shoulder is paid attention. This is because the shoulder rehabilitation requires a larger moving area and larger generated force to lift up whole arm. Fig. 5 shows a sample of the actual rehabilitation device for shoulder in a certain department of rehabilitation of Japanese hospital[14]. The device is used to improve the moving area of the shoulder of patients by themselves. The left photograph in Fig. 5 shows the rehabilitation device using a pulley and a rope with handles to lift up the injured arm by pulling by using of the opposite normal arm. The right photograph in Fig. 5 shows the device using rotational rod with a handle to give a rotational motion to shoulders. Both devices are driven by patients. These devices are useful to apply the medical treatment for patients in the case when patients can drive them. If the patient doesn't have enough ability to drive it, a device that can give passive exercise is required. In the case using a rigid device that gives the passive exercise for human shoulder, the device must be controlled so as to track a complex orbit of the holding position based on the patient joint's moving area and moving direction. By considering these requirements, the rigid type rehabilitation such as robot arm is needed to measure the magnitude and direction of acting pulling force to the patient. In addition, it must be also required the pre-calculation of moving orbit based on the personal moving area of patient's joint. It becomes very difficult to realize a home rehabilitation device that can be used by patient without specialist. If the device has a tolerance for moving area of the arm and shoulder, a simple and low-cost rehabilitation device can be realized.

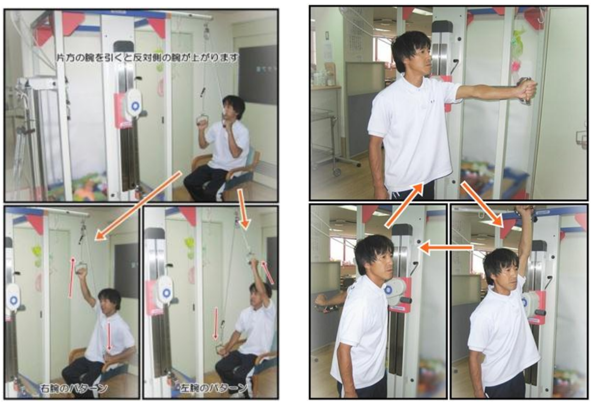


Figure 5. A sample of rehabilitation device for shoulder in a hospital[14].

B. Construction of Simple Rehabilitation Device

A simple rehabilitation device using the tested actuator that has a tolerance based on its flexible rod is proposed and tested. Fig. 6 shows the construction of the tested simple rehabilitation device. The tested device consists of two flexible linear stepping actuators and a flexible rod. Both actuators use one flexible rod. Each actuator is fixed on an iron frame so that each direction of the actuator meets face to face. To simplify the moving system of the device, a simplified linear stepping actuator as shown in Fig. 7 is used. Compared with the previous actuator as shown in Fig.1, the re-designed actuator uses one kind of pneumatic cylinder with stroke of 50 mm. Two stages with the pneumatic chuck is used in the actuator. In addition, both ends of the actuator have a mechanical guide with an inner bore of 22 mm to keep a flexible rod straight. By removing the three pneumatic cylinders and a chuck, the mass of the actuator is reduces from 700 g to 540 g. The number of the required valve for each actuator can be reduced from seven to four. It means that the estimated cost of one actuator including valves can be reduced from 430 USD to 240 USD. It can be confirmed that the redesigned actuator is more suitable to realize a low-cost home rehabilitation device.

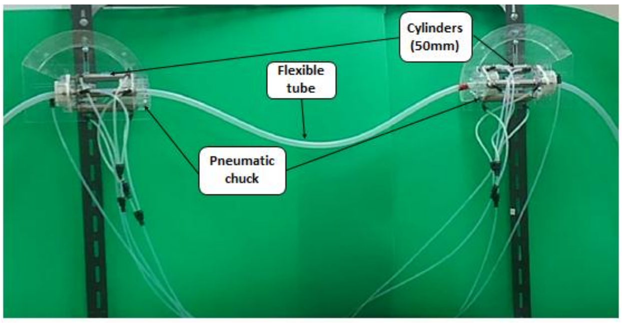


Figure 6. Overview of the tested simple rehabilitation device using two flexible linear stepping actuators.

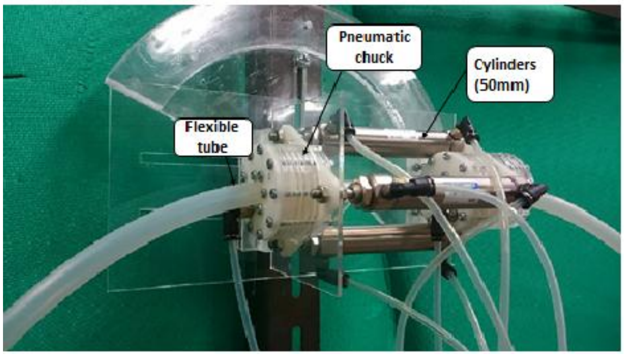


Figure 7. Overview of the simplified linear stepping actuator.

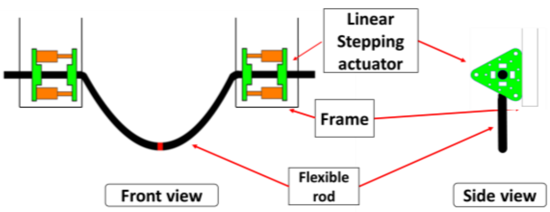


Figure 8. Schematic diagram of the tested device set on the frame.

Fig. 8 shows the schematic diagram of the tested device set on the frame. Fig.8 also shows the front and side view image of the device when both actuators set on the same plate. In the device, the loosing flexible rod can easily rotate around center of the actuator. It means that the tested device has a tolerance.

C. Fundamental Operations of the Tested Device

Fig. 9 shows a fundamental operations of the tested device. As the fundamental operations, the device has four moving motion such as a moving "Downward", a lifting "Upward", a moving "Leftward " or " Rightward" and a moving "Obliquely". The moving "Downward" can be realized by releasing the flexible rod so that both actuators push the rod toward the center. The rod grasped by hand is automatically moved downward because of a load of human arm. The lifting "Upward" motion can be realized to pull the rod by using both actuators. The moving "Leftward" can be realized by applying the pulling motion to the left side actuator and pushing motion to the right side actuator. In the case of moving "Rightward", it can be realized by giving the opposite motion for each actuator. In addition, the moving "Obliquely" can be realized by giving pulling motion to an either actuator under the condition when the other actuator is holding the rod. The amount of the available motions are eight motions that include such as a moving "left obliquely upward".

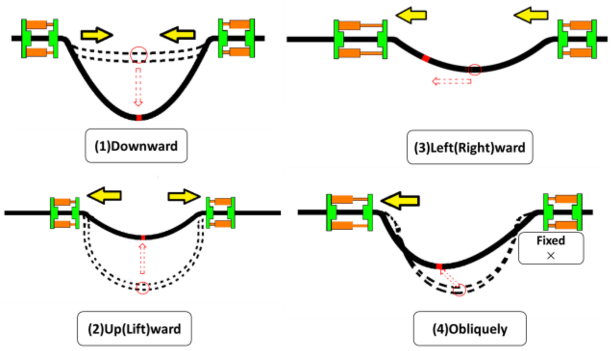


Figure 9. Fundamental operations of the simple rehabilitation device.

IV. Control System and Sequential Control

A. Control System of the Rehabilitation Device

Fig. 10 shows the schematic diagram of the motion control system of the tested rehabilitation device. The device consists of the tested rehabilitation device, an embedded controller (Renesas Electronics Co. Ltd., SH7125) and eight on/off control valves (Koganei Co. Ltd., G010HE). In Fig.10, blue and red arrows show the air flow and electric signal, respectively. The motion control of the flexible rod is as follows. According to desired sequential motion of the device, the valve is selected to drive for each timing. As each liner stepping actuator can only move every 50 mm, the motion of the rod can give stepwise motion to the patient's arm and shoulder. This stepping motion can be changed by the cylinder's stroke. The moving speed depends on the input flow rate to the cylinder. By using a typical pneumatic speed controller that is a fluidic variable resistance, the speed of the actuator can be easily controlled. In addition, the force of the motion can be also controlled by changing the supply pressure of the device by using the typical pressure regulator. It means that the user can easily adjust the moving speed and the applied force of the passive exercise by turning the knob of the speed controller and regulator. It also means that the device can be adjusted by user without special knowledge of engineering. In addition, the device can secure safety because patients can immediately release the rod as soon as they feel danger. Passive exercise of the device will be able to be also easily selected by changing pre-programmed sequential data using buttons etc.

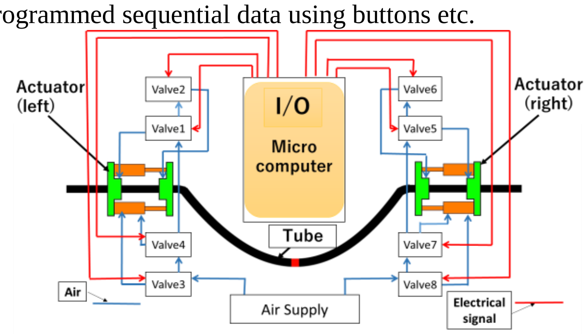


Figure 10. Schematic diagram of motion control system of the rehabilitation device.

B. *Driving Patten of the Actuator*

In order to drive the actuator in the device, a driving pattern is important so as to prevent the slip of the actuator. In particular, the timing of change to drive pneumatic chuck is directly related to slip of the rod. In the preliminary driving test of the actuator, the driving pattern of the actuator for moving upward was investigated. Fig. 11 shows the time chart of each valve when the device gives a lifting motion. In the experiment, the load of 49 N is applied to the rod. In Fig. 11, the valve number shows the same valve number in the control system as shown in Fig.10. In the experiment, the overlap time is selected so as to prevent slip of the rod is investigated by trial and errors. As a result of the preliminary experiment, the overlap time of holding and releasing of pneumatic chucks of 0.05 s is selected. The overlap time depends on the dynamics of the chuck driven by the output flowrate of the valve. This overlap time between holding and releasing is also applied when the motion of the device is changed such as a switching from the lifting motion to the moving leftward.

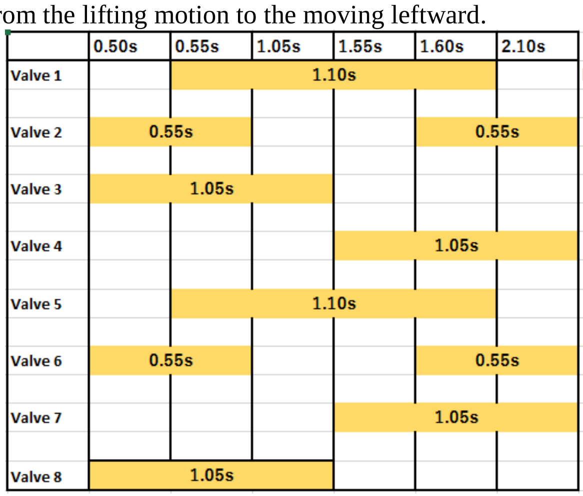


Figure 11. Time chart of the driving valves for lifting upward.

C. *Experimental Results*

In order to confirm the validity of the tested device, the driving test of the device is carried out. Fig. 12 shows the transient view of the device under the condition when a load of 19.6 N is applied to the rod. The applied sequential motion is as follows. First, the device gives 2 times downward motions to the rod. Next it gives 2 times lifting motions. And, 4 times moving leftward are carried out. From Fig.12, it can be seen that the device has an ability to drive the load of 19.6 N according to the sequential motion. It can be also found that the height of holding position after this journey is almost same as the height of starting position. It means that here is little slip on each motion.

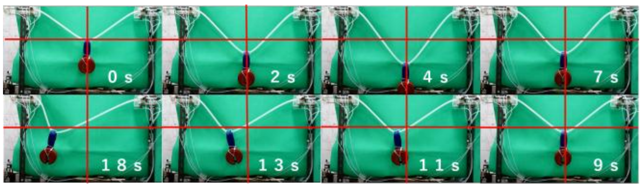
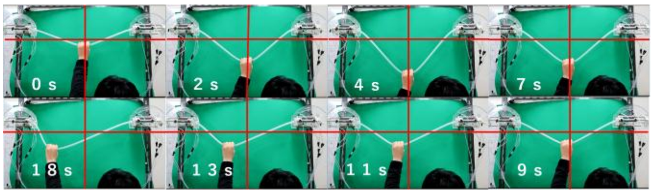
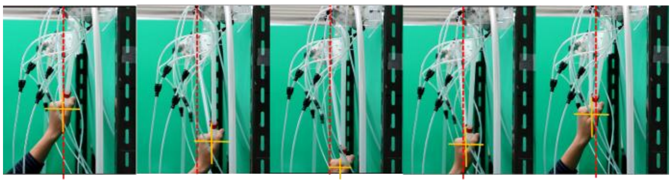


Figure 12. Transient view of the motion of the tested device with load of 19.6 N



a) Front view



b) Side view

Figure 13. Transient view of the passive exercise for shoulder.

Fig. 13 (a) and (b) show the transient view of rehabilitation motion under the condition when a user holds the rod. In the experiment, the same driving pattern is given to the device. Fig.13 (a) shows the front view of the experiment. Fig.13 (b) shows the side view. From the side view, it can be seen that the holding position is naturally changed according to the movement of the upper limb. It means that the device has the tolerance that is required as a human-friendly driving device.

V. Conclusions

In order to develop a low-cost home rehabilitation device that the user can use it at home without special knowledge, the simple rehabilitation device using two flexible linear stepping actuators is proposed and tested. To prevent the slip of the flexible rod when the motion of the actuator is changed, the suitable driving pattern of the pneumatic chuck and pneumatic cylinders in the actuator is investigated. The driving test of the tested device using the obtained suitable overlap timing of pneumatic chuck according to the sequential motion control is carried out. As a result, it can be confirmed that the tested device can give passive exercise to user's shoulder without slipping the flexible rod. It can be concluded that the tested device is valid to be applied to the home rehabilitation device because of its enough force and moving area to drive the shoulder with fundamental safety based on its tolerance and flexibility.

As future work, the passive exercise using the tested simple rehabilitation device is going to be applied as a real physical therapy device.

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