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Paper:

Development of Power Assist Wear Using Pneumatic Rubber Artificial Muscles

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In the future, when the average age of the members of society becomes advanced, an innovative technology to assist the activities of daily living of elderly and disabled people and to assist in the heavy work in nursing will be desired. To develop such a technology, an actuator that is safe and user-friendly is required. It should be small, lightweight, and sufficiently soft. Such an actuator is available in artificial muscle made of pneumatic rubber. We have developed some types of pneumatic rubber artificial muscles and applied them to wearable power assist devices. A wearable power assist device is fitted to the human body to assist the power of muscles that support the activities of daily living, rehabilitation, training, and so on.

In this paper, some types of pneumatic rubber artificial muscles developed and manufactured in our laboratory are presented. Furthermore, two kinds of wearable power assist devices driven by the rubber artificial muscles are described. Finally, some evaluations clarify the effectiveness of pneumatic rubber artificial muscle for innovative human assistance technologies.

Keywords: wearable robot, power assist, pneumatics, rubber artificial muscle

1. Introduction

Robots are expected to help make one's life less troubled and more comfortable in the society of the future, a society with fewer children and more elderly people. It will lead to a big improvement in the QOL (Quality of Life) if a human-friendly robot that supports the elderly and physically handicapped in their daily life and social activities, rehabilitation, etc. can be created.

Research work on such a human assistance robot also is being done in the author's laboratory. The robot developed is fitted to the body to support body movements by assisting and enhancing the power of the muscles. This kind of robot is called a wearable power assist robot, and such robots are being developed in research laboratories in the United States and Japan. However, they are not yet ready for practical use. This paper describes a wearable power assist device we have developed.

2. Background of Research

Physically handicapped, elderly, or disabled people can expect to live more independent lives by using this kind of device. Although research into wearable power assist devices was done for a while in the 1960's, the devices were extremely large, heavy, and impractical. Little research was done in this field afterwards. Now, wearable power assist technologies have become practical through the miniaturization of electronic components and the development of a small and lightweight actuator. Their applications to welfare fields have gathered attention.

A wearable device that it is safe and user-friendly is essential. Its components should be small, lightweight, and soft, and it should have moderate output power. In the authors' laboratories, we have focused on pneumatic rubber artificial muscle as an actuator that satisfies these requirements. We have developed some new rubber artificial muscles, and we have manufactured some wearable power assist devices on an experimental basis.

3. Pneumatic Rubber Muscle

McKibben rubber muscle is a typical pneumatic rubber artificial muscle [1]. It can generate a large force of contraction, but its contraction rate (about 30%) is smaller than that of human muscle (about 50%). To assist the rotational motion of human joints with such a linear artificial muscle, a mechanism for securing the sufficient range of motion and the conversion of the force generated to the joint torque is required. Such a mechanism threatens to reduce the size and weight advantages of the device. McKibben rubber muscle, which can generate a large amount of force, is suitable for devices needing a large amount of force, such as devices to assist one in standing up [2]. However, for devices that assist the motion of a finger or upper arm, as they do not need to be so powerful, an assist device not needing a torque conversion mechanism is desired to keep it small and lightweight.

To these ends, two kinds of curved pneumatic rubber artificial muscles that perform the curve operation by supplying compressed air have recently been developed, and they have been employed in power assist devices that assist the operation of the fingers and elbow. These devices can be composed of soft materials such as rubber,

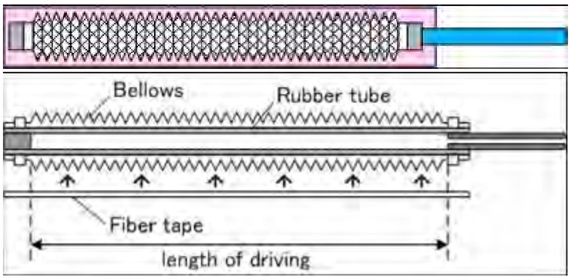


Fig. 1. Curved rubber artificial muscle.

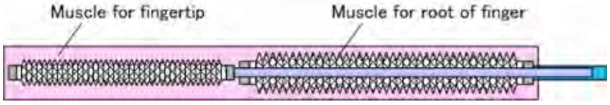


Fig. 2. Two-joint curved artificial muscle.

polyester fiber, and cloth, and they can be fitted to the human body like clothes. The authors call such wearable power assist devices "power assist wear."

4. Power Assist Glove

It is a wearable power assist device that assists the bending motion and increases the grasping force of the fingers through the installation of curved pneumatic rubber artificial muscle on the upper side of each of the five fingers of a glove. The glove works as a mechanical interface to transmit the generated force of the artificial muscles to the human fingers.

4.1. Curved Rubber Artificial Muscle

Figure 1 shows the structure of the curved pneumatic rubber artificial muscle. It is composed of a rubber tube covered with a bellows sleeve which extends or contracts only axially. By inhibiting the extension of one side with the fiber reinforcement, the bending motion toward the reinforcement occurs by pumping compressed air into the rubber tube.

Figure 2 shows the structure of two-joint curved pneumatic rubber muscle. Two curved rubber muscles of different diameters are connected in series, the basic structure of each of which is the same as that seen in **Fig. 1**. The muscle for the finger tip is composed of a rubber tube with an inside diameter of 3.0 mm and an outside diameter of 4.5 mm. The bellows have an inside diameter of 7.5 mm and an outside diameter of 10.0 mm. The muscle for the root of the finger is composed of a rubber tube with an inside diameter of 6.4 mm and an outside diameter 8.4 mm. The bellows have an inside diameter of 12.0 mm and an outside diameter of 16.0 mm.

4.2. Two-Joint Power Assist Glove

A one-joint power assist glove with one artificial muscle in each finger was developed, and its utility was confirmed [3]. So far, it has the problem of being unsuitable for the pinch operation.

Fig. 3. Two-joint power assist glove.

(a) Grasp operation (b) Pinch operation

Fig. 4. Operation of two-joint power assist glove.

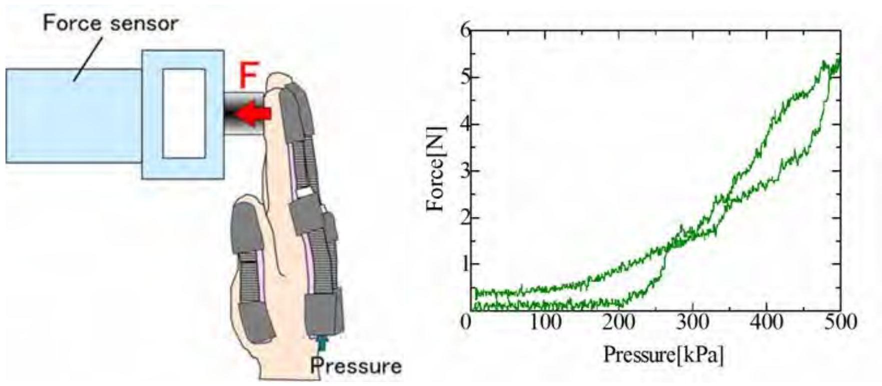
To deal with this problem, the two-joint power assist glove shown in **Fig. 3** has been developed. A glove made of leather is used as an interface to transmit the generated torque of the artificial muscle to the human finger. The artificial muscles are installed along the top of each finger to assist the bending motion. The extension of the finger is assisted by the restoration torque of the artificial muscle when releasing the pressure. The total weight of the glove is about 120 g.

Figure 4 shows the grasp operation and the pinch operation assisted by this glove. The tip and the base of the finger can be operated separately. In the grasp operation, both artificial muscles in the tip and base of the fingers are pressurized. In the pinch operation, only the muscle in the base of the finger is pressurized to hold the finger tip straight as shown in **Fig. 4(b)**. By controlling the pressure supply to the artificial muscles in the tips and bases of the fingers individually, various operations can be assisted. The force of assistance can be controlled by adjusting the pressure to each muscle.

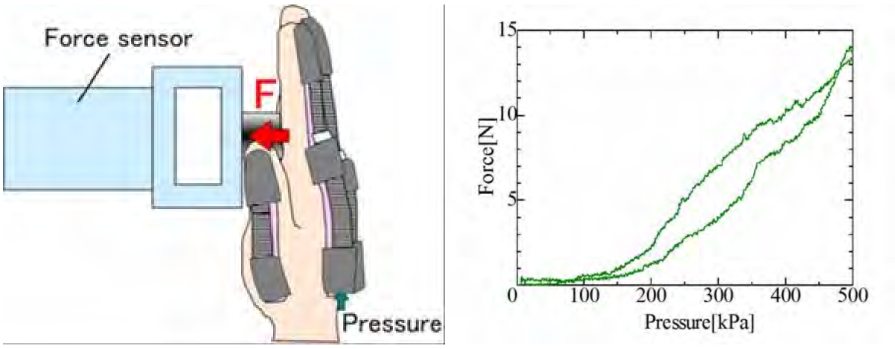
4.3. Performance of Power Assist Glove

The generated force of the power assist glove is examined. The glove is fitted to the human subject in the initial state of having no pressure in the rubber artificial muscle. The artificial muscle at the base of the forefinger is pressurized to examine the force generated at the finger tip in the pinch operation and at the base of the finger in the grasp operation.

Figures 5(a) and **(b)** show the measured forces at the tip and base of the finger, respectively. When the artificial muscle at the base of the forefinger is pressurized at 500 kPa, the maximum forces generated are 5.7 N at



(a) Tip of finger



(b) Root of finger

Fig. 5. Generated force of power assist glove.

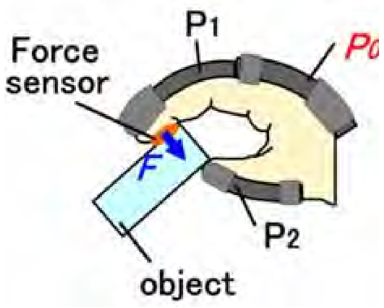


Fig. 6. Measurement of pinch force assisting.

the tip and 14 N at the base of the finger. These forces are large enough for the glove to be used for power assistance, rehabilitation, and some work assistance.

The force generated at the tip of the forefinger in the pinch operation is measured with a thin tactile force sensor at the finger tip, as shown in **Fig. 6**. In the measurement, the human subject does not generate any personal muscle force. Four objects 5, 10, 20 and 40 mm in thickness are pinched. The inner pressure of each rubber muscle is adjusted to $P_1 = P_0 - 50$ kPa, $P_2 = P_0 - 150$ kPa.

Figure 7 shows the force for P_0 from 0 kPa to 500 kPa. Although the force tends to decrease somewhat for the thinner objects, a pinch force of about 4 N can be attained by wearing this glove pressurized to at $P_0 = 500$ kPa. Considering the pinch force of a typical male is about 20 N to 25 N, this glove is successfully assists the pinch operation.

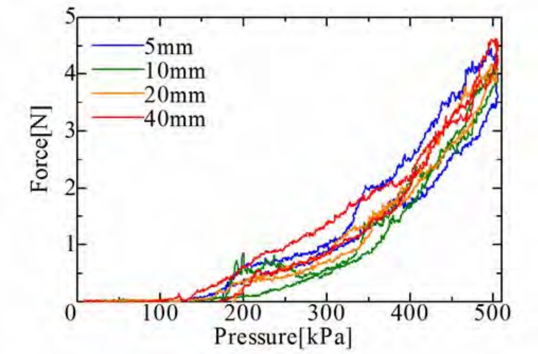


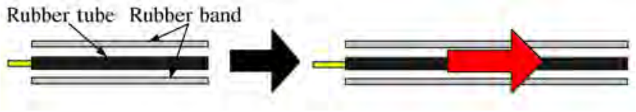
Fig. 7. Generated force of glove in pinch operation.

5. Elbow Power Assist Wear

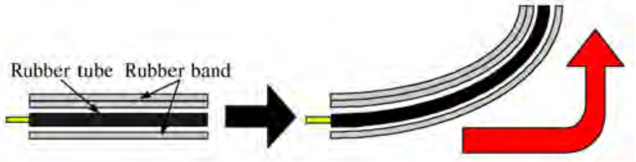
A sheet-like curved pneumatic rubber artificial muscle has recently been developed, and using this muscle, a power assist device to assist the bending motion of the elbow has been developed [4].

5.1. Sheet-Like Curved Artificial Muscle

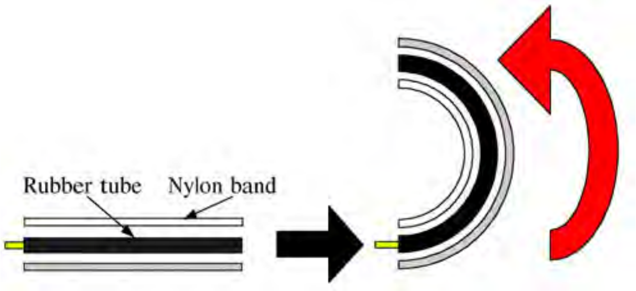
The device is composed of a rubber tube sandwiched between two upper and lower sheets sutured together as shown in **Fig. 8**. One end of the rubber tube is sealed up; the other is connected to the pressure control valve. By using an elastic sheet (fabric rubber) for two upper and lower sheets that can extend, when the rubber tube is



(a) Extension operation



(b) Extension and curve operation



(c) Curve operation

Fig. 8. Operation of sheet-like curved muscle.

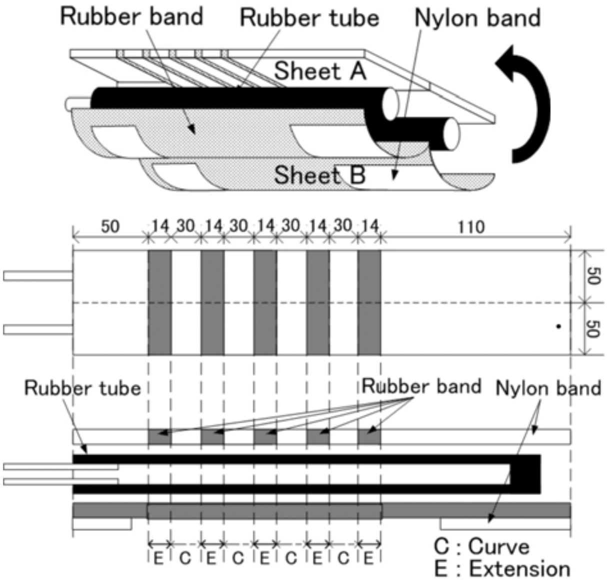
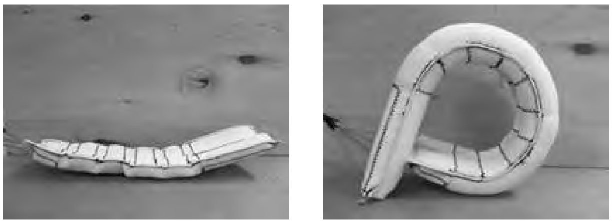


Fig. 9. Structure of sheet-like curved muscle for elbow power assist wear.



(a) Before pressurized (b) Pressurized to 250 kPa

Fig. 10. Operation of sheet-like artificial muscle.

(a) Before pressurized (b) Pressurized to 250 kPa

Fig. 11. Operation of power assist wear for elbows.

pressurized, extension in the axial direction is obtained.

Three operations can be achieved by differing the amount of extension of both sheets due to the difference in the number of sheets or the elasticity of the sheets. **Fig. 8(a)** shows the use of the same number of sheets on both sides. Since the amounts of extension are the same, linear extension in the axial direction is caused. When there is a difference in the number of upper and lower sheets, the difference in the amounts of extension causes the extension and curved motion shown in **Fig. 8(b)**. In **Fig. 8(c)**, material that does not extend in the axial direction (nylon band) is used in the upper sheet; only the curving operation occurs when the rubber tube is pressurized. Through the combination of these operations, power assistance along the movement of the human body can be obtained.

Figure 9 shows the structure of manufactured sheet-like curved rubber muscle. Two rubber tubes are sandwiched between two sheets, A and B. Sheet A is composed of an alternate arrangement of rubber bands and nylon bands. Sheet B is composed of rubber band, except that both ends are nylon band. Such a structure adjusts to the movement of the human body.

5.2. Structure and Operation of Power Assist Wear

The artificial muscle used for the elbow power assist wear is 350 mm in total length and 100 mm in width. **Fig. 10** shows the operation of manufactured artificial muscle. The maximum bend in the angle of the elbow joint is about 145°. The manufactured artificial muscle can bend toward this angle by pressurizing the artificial muscle to about 120 kPa. It also extends about 60 mm axially under the same pressure.

Figure 11 shows the operation of the elbow power assist wear. Soft equipment composed of cloth and rubberized fabric is used to transmit the generated force of the muscle to the human elbow. Moreover, by installing the slide part between the artificial muscle and the device, the artificial muscle can extend axially for a smooth assist operation. The weight of the artificial muscle is 175 g, and the total weight including the equipment is 365 g. It is light enough for people to wear.

5.3. Fundamental Characteristics

The generated torque of the manufactured elbow power assist device is measured by using the elbow joint model with one degree of freedom, as shown in **Fig. 12**.

Figure 13 shows the measured torque, which is calculated from the generated force F at the tip of the device for

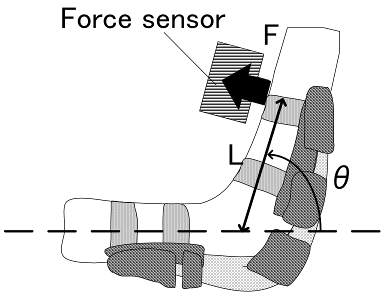


Fig. 12. Measurement of generated torque of power assist wear.

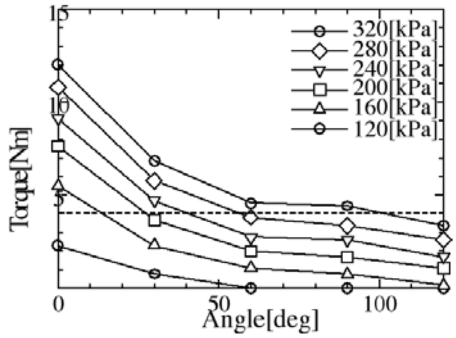


Fig. 13. Generated torque of power assist wear.

angle θ from 0° to 120°. The distance L from the center of rotation of the elbow model to the point at which force is measured is 0.155 m. A torque necessary to hold the weight of a typical adult male's forearm is about 4 Nm; when the device is pressurized to 320 kPa, it can hold the weight and assist the bending of the forearm over a range of about a 100° angle or less.

5.4. Effect of Power Assistance

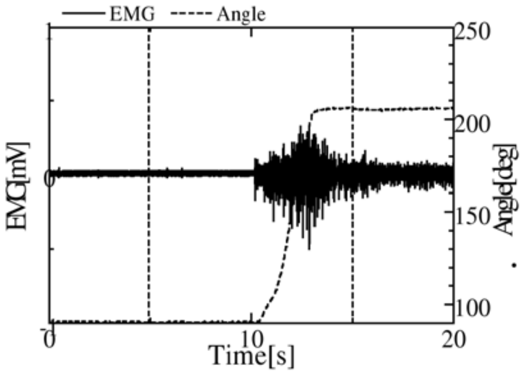
To evaluate the effect of power assistance, the angle of the bend and the myogenic voltage of the biceps brachii are measured before and after the human subject dons the wear. The bending operation of the elbow starts with the forearm extended forward horizontally. The pressure the artificial muscle begins the operation with is set to the initial pressure for the muscle, and the experiment is conducted according to the following steps.

1) From 0 s to 5 s, the device is pressurized to the initial pressure of 80 kPa.

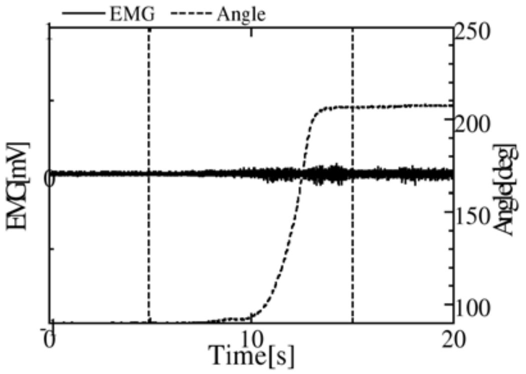
2) From 5 s to 15 s, it is pressurized to 320 kPa in a ramp mode when the person is relaxing.

3) From 15 s to 20 s, the assistance is maintained while the human subject relaxes.

Figure 14 shows the experimental results, where the solid lines show the myogenic voltage and the broken lines show the angle of the bend. The maximum angle in the bend of the elbow of the human subject is about 120°. A relative angle between the forearm and the body is about 210° (The angle of the elbow joint is about 120°). A range of assistance of about 100% is possible compared with the maximum angle of bend of the subject. It can be confirmed that the load of the human elbow can be reduced through the use of the wearable power assist device as evidenced by the decrease in the myogenic voltage owing to the generated torque of the wear.



(a) Without assistance



(b) With assistance

Fig. 14. Effect of power assistance for elbows.

6. Conclusions

We have described the structure and fundamental characteristics of two kinds of newly developed, curved pneumatic rubber artificial muscles, as well as the power assist glove and the elbow power assist wear composed of these artificial muscles. Torque conversion mechanisms, such as the belt and pulley required when the McKibben's linear artificial muscle is used, becomes unnecessary by when curved muscle is used. As a result, small and lightweight wearable power assistance devices become possible. Moreover, clothes similar in function to the soft power assist wearable device can be made using soft materials, such as rubber and cloth, as shown in **Fig. 15**. They can be comfortable to wear for extended periods or even all the time.

The proposed "power assist wear" is expected to become a useful wearable power assist device.

To advance the practical use of these wearable power assistance devices in the future, it will be necessary to clarify the structures of the devices suitable to be worn on different parts of the human body. The pneumatic energy source is also an important issue. When the area of the device is limited, the pneumatic energy can be supplied

Fig. 15. Power assistance device worn like clothing.

through a tube from a fixed air compressor. However, ideally, a small, lightweight, quiet, and wearable air compressor is desired. The development of such an energy source is also anticipated.

Finally, we would like to add that this research was executed as 16078210, “Pneumatic Soft Actuator for Human Friendly Mechanism,” in the research project “Next-Generation Actuators Leading Breakthroughs,” funded by the MEXT Grant-in Aid for Scientific Research on Priority Areas.

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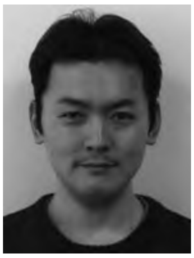

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