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Pneumatic Soft Actuator for Human Assist Technology

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ABSTRACT

In the coming advanced age society, an innovative technology to assist the activities of daily living of elderly and disabled people and the heavy work in nursing is desired. To develop such a technology, an actuator safe and friendly for human is required. It should be small, lightweight and has to provide a proper softness. We call such an actuator *soft actuator*. A pneumatic rubber artificial muscle is one of typical soft actuators, which is useful for the human assist technology. We have developed some types of pneumatic rubber artificial muscles and applied them to human friendly soft mechanisms and wearable power assist devices. Since these mechanism and devices directly act on the human body, the human friendliness is essentially important. A wearable power assist device is equipped to the human body to assist the muscular force, which supports activities of daily living, rehabilitation, heavy working, training and so on.
In this paper, some types of rubber muscles developed and manufactured in our laboratory are introduced. A soft robot hand for wiping the human body and a parallel manipulator for the wrist rehabilitation are described as soft mechanisms. Further, a wearable power assist glove and a power assist splint for upper arm are shown. Some evaluations clarify the effectiveness of pneumatic soft actuator for an innovative human assist technology.

KEY WORDS

Pneumatics, Rubber artificial muscle, Soft mechanism, Wearable power assist, Human friendly robot

INTRODUCTION

In the coming advanced age and few-birthrate society, there may not be enough working people in various fields such as medical welfare, agriculture and so on. Especially, the increase of elderly and the lack of caregiver will become a serious problem. To overcome the problem it is expected to introduce a machine or robot to assist the elderly, disabled people, caregiver, nurse, hard worker and so on. Such a human assist technology has become of major interest recently. The researchers in robotics and mechatronics have become interested in the relation between human and machine. Some types of human friendly robots have been exhibited in EXPO 2005 AICHI JAPAN. Since these kinds of machines or robots have to work near the human or directly act on the human body, both safety and friendliness for human are essentially important.

To satisfy these requirements, an actuator safe and friendly for human is desired. It should be small, lightweight and has to provide a proper softness. As such an actuator we have remarked the availability of pneumatic soft actuator. A pneumatic rubber artificial muscle may be very useful as one of soft actuators. We have developed and manufactured some types of pneumatic rubber artificial muscles. Using these actuators, a pneumatic soft mechanism and a wearable power assist devices have been developed. As a pneumatic soft mechanism, a soft robot hand and a wrist rehabilitation device have been developed. A wearable power assist glove and a power assist splint for upper arm are developed.

This paper firstly describes the structure and the fundamental characteristics of some developed pneumatic rubber artificial muscles. Next, the structure and the performance of soft mechanisms and wearable power assist devices are shown, of which the availability are evaluated through some experiments.

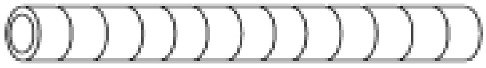
PNEUMATIC SOFT ACTUATOR

A conventional pneumatic actuator such as a pneumatic cylinder is widely used for not only simple positioning, but also a force control, for example, clamping and so on because of its inherent compliance from the air compressibility. Since the body of conventional actuator is usually made of a rigid material, there is no flexibility in directions except movable axis of the actuator.

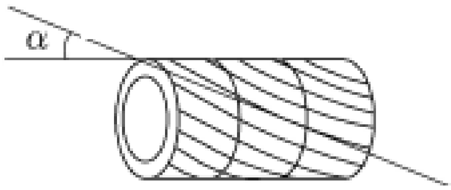
On the contrary, we call an actuator *soft actuator* of which body is soft as well as the motion property. It has passive compliance in the all directions. A pneumatic soft actuator is generally constructed with tube or balloon made of elastic material as rubber, driven with the pressure control. The fundamental operation depends on both expansion and contraction of elastic tube or balloon with the inner pressure control.

Various motions can be obtained by changing the stiffness in the specified directions with a fiber and so on. Figure 1 shows a structure of fiber reinforcement type actuator. In Figure 1(a), a rubber tube is reinforced around the circumstance with fibers. When compressed air is supplied into the rubber tube, because the expansion in the radius direction is restricted with fibers, only the extension in the axial direction is obtained from the inner pressure increase. Figure 1(b) shows the fiber reinforcement of radius direction and axial direction with the angle α. The pressure increase makes the tube rotate around the axial center line. A McKibben type rubber artificial muscle is one of typical fiber reinforcement actuators.

Figure 2 shows an example of pneumatic soft actuator made of silicone rubber [1]. This actuator can realize the rotary operation around the intersection of two side plates owing to the fiber reinforcement in the radial and height directions and the high stiffness produced by thickness of side plates.



(a) Extended motion



(b) Rotational motion

Figure 1 Fiber reinforcement

Figure 2 Rotary type pneumatic soft actuator

PNEUMATIC RUBBER ARTIFICIAL MUSCLE

A McKibben type pneumatic rubber artificial muscle is well known. Now, a few companies manufacture commercially available one [2]. We have developed some new types of pneumatic rubber muscle in addition to the McKibben type [3].

Contracted linear type

Figure 3 shows a conventional McKibben type rubber muscle, which is manufactured by covering the surrounding of a rubber tube with fiber net. It may be called a contracted linear type. By pressurizing the rubber tube, the muscle generates the axial contraction force. We can manufacture the rubber muscle with an arbitrary size using commercially available rubber tube and polyester fiber net. Figure 4 shows the fundamental characteristics of the manufactured rubber muscle comprising a rubber tube with an outer diameter of 11.6mm, an inner one of 8.0mm, and a length of 793mm when not pressurized. The contraction rate is saturated to about 25%. The saturated value depends on the cross angle of fibers. When pressurizing the rubber tube to 600kPa, the contraction force reaches 340N. The performance is equivalent to the commercially products.

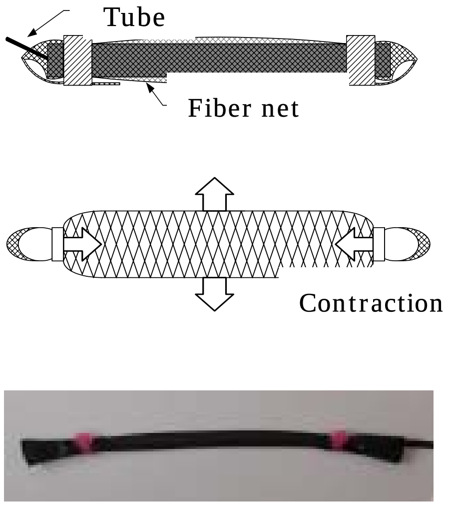


Figure 3 McKibben type rubber muscle

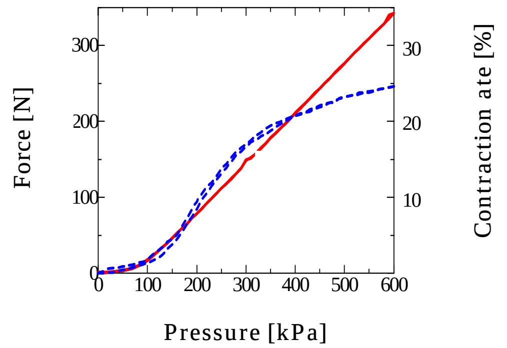


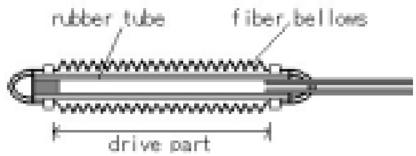
Figure 4 Fundamental characteristics

Extended linear type

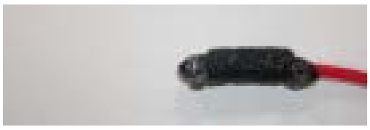
Figure 5 shows the structure of extended linear type rubber muscle. It consists of a rubber tube and a polyester fiber bellows. When the compressed air is supplied into the rubber tube, the muscle extends to the axial direction as shown in Figure 5(c). By decreasing the inner pressure, the muscle is made restitution as shown in Figure 5(b). The manufactured muscle is composed of a rubber tube with outer and inner diameter 8.4, 6[mm], and of a polyester bellows with outer and inner diameter 16, 13[mm]. The initial length of drive part is 40[mm].

Figure 6 shows the fundamental characteristics. Figure 6(a) shows the relation between the inner pressure and the extended length. The maximum extended length is about 76[mm] at 500[kPa]. Figure 6(b) shows the restitution force of the muscle. The restitution force is measured when the supplied inner pressure is 0[kPa].

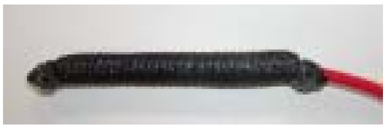
A contracted type (McKibben type) rubber muscle with the same size as the extended type muscle shown in Figure 5 is manufactured to compare both performances. The maximum restitution force of the extended type is smaller than the maximum contraction force of contracted type (McKibben type), on the contrary, an extension rate of extended type is larger than the contraction rate of the McKibben type. The extended type is better to achieve the large movable range than McKibben type.



(a) Structure

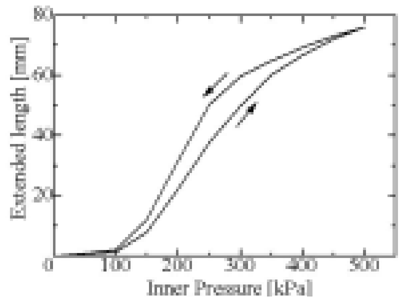


(b) Initial state (0kPa)

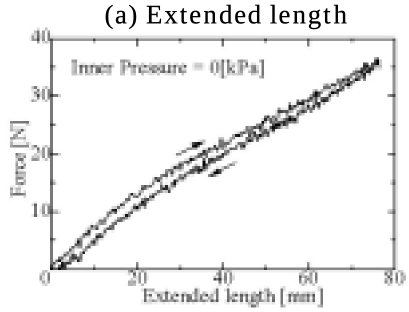


(c) Pressurized state (500kPa)

Figure 5 Extended linear type muscle



(a) Extended length



(b) Restitution force

Figure 6 Fundamental characteristics

Contracted curved type

Figure 7 shows a contracted curved type pneumatic rubber muscle, which is constructed by reinforcing one side of a McKibben type rubber muscle with an elastic acrylic sheet. When the rubber tube is pressurized, only the top side is contracted by the effect of reinforcement of the bottom side. As a result, the upward curved motion can be realized as shown in Figure 7(b). By increasing the stiffness of the elastic sheet, the recovery force increases but the generated curved force decreases.

Figure 8 shows a fundamental characteristic of manufactured rubber muscle composed of parallel two rubber tubes with outer and inner diameters of 11.6[mm] and 8.0[mm], respectively. When the muscle is pressurized 500[kPa], the curved angle reaches 126 [degree], the maximum curved force of 78[N] can be generated.

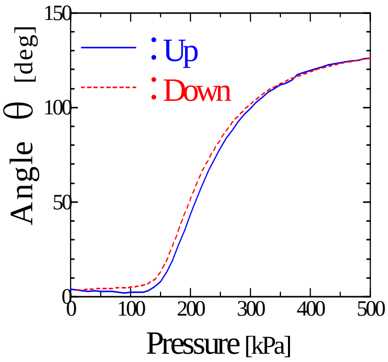
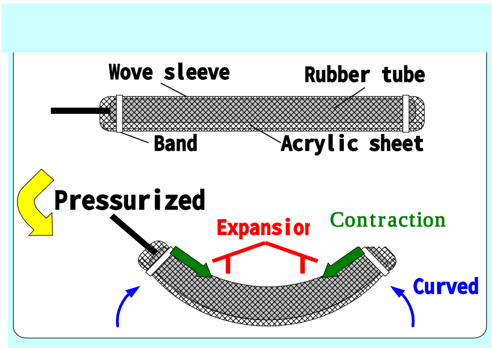


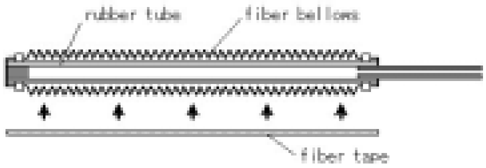
Figure 8 Fundamental characteristics



(a) Operational principle

(b) Curved configuration

Figure 7 Contracted curved type muscle



(a) Structure

(b) Configuration

(c) Curved motion

Figure 9 Extended curved type muscle

Extended curved type

Figure 9 shows an extended curved type rubber muscle consisting of a rubber tube with outer and inner diameters of 8.4, 6[mm], and a polyester bellows with the outer and inner diameters of 16, 13[mm]. To inhibit the extension to the axial direction of bottom side, the polyester fiber bellows is reinforced with a fiber tape. Three muscles with the length of 140, 120 and 80[mm] are manufactured. By the reinforcement, when compressed pressure air is supplied into the rubber muscle, the rubber muscle can curve to the reinforced side as shown in Figure 9(c). Figure 10 shows the measured fundamental characteristics of three rubber muscles. The generated force is almost independent of the length of muscle. The generated force for the supply pressure of 500[kPa] is about 23[N], and the relation between the force and the pressure is almost linear above the inner pressure of 150[kPa].

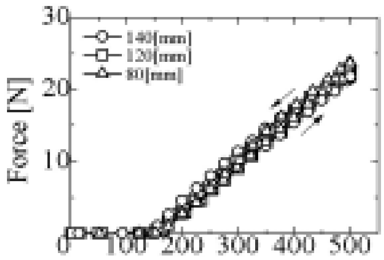


Figure 10 Fundamental characteristics

HUMAN FRIENDLY SOFT MECHANISM

The development of machines or robots to assist a human activity in nursing, welfare and daily living has recently become an important subject. Such machines or robots are required safety, friendliness for human and soft motion similar to human rather than conventional high speed and high accuracy performance. In order to realize such a human friendliness, it is effective to use an inherent soft mechanism. We call it *human friendly soft mechanism* of which some examples are described.

Soft robot hand

Figure 11 shows a soft hand consisting of soft fingers and the contracted linear type rubber muscles as shown in Figure 3 [4]. The mass of hand is 900[g]. The length is 185[mm]. The soft finger has three joints as shown in Figure 12. A rotary-type pneumatic soft actuator similar to Figure 1 is put at intervals of 25[mm]. The disposition of linear type muscles is decided by referring the human muscles. This hand can operate almost same as a human hand. Pressurizing the rotary-type actuator, the finger bends. The linear type rubber muscles drive the wrist of hand.

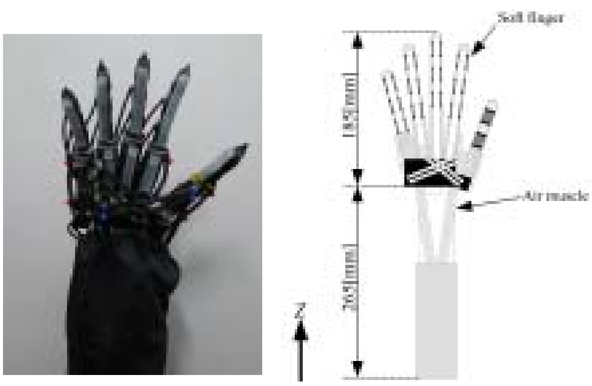


Figure 11 Soft robot hand

Because the pneumatic soft actuator expands or contracts by itself being different from a conventional hard actuator, mechanical components such as bearing and joint is not required. By mounting a pneumatic soft actuator directly at joint, the mechanism can become simple and small. Also, since the hand is driven with only pneumatic power, it can operate under water without waterproofing.

(a) Initial state (b) Pressurized state

Figure 12 Soft finger

Figure 13 shows an application of the hand to a wipe motion for human arm. The soft hand is moved forth and back on the human arm in the direction of the human arm length with a speed of 10[mm/s]. A soft tactile sensor shown in Figure 14 is attached to the end of each finger to detect the contact force. The sensor is made of a cylindrical silicone rubber with an outer diameter of 16[mm], an inner diameter of 15[mm]. When the external force is applied to the upper plate, the inner pressure of sensor is increased according to the compression of cylindrical silicone rubber chamber. Tactile information is detected by measuring the inner pressure change with a pressure sensor. In the wipe motion of Figure 13, the contact force is feedback controlled with this sensor for the desired force of 1.5[N]. The accurate force control can be achieved.

Figure 13 Wipe motion with soft hand

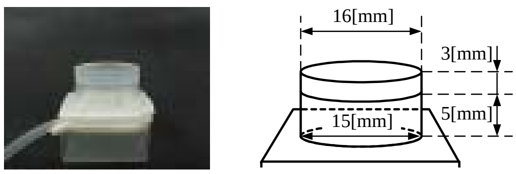


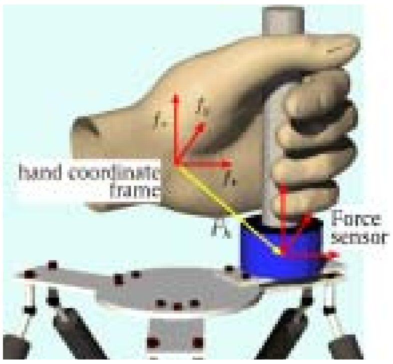
Figure 14 Soft tactile sensor

Parallel manipulator

Since joints of human have multiple degrees of freedom, a rehabilitation machine for these joints is desired to provide multiple degrees of freedom. Further, it must be built with a human friendly soft mechanism. To satisfy both requirements, we have proposed to use a pneumatic parallel manipulator as a rehabilitation machine [5].

Figure 15(a) shows the pneumatic parallel manipulator for a wrist rehabilitation exercise. Six pneumatic cylinders are used as driving actuators to construct Stewart type platform. Figure 15(b) shows a view of operation. A patient put his/her forearm above the upper platform along the *x* axis of manipulator and trains rehabilitation exercises by holding a bar attached to a 6-axes force/moment sensor equipped on the upper platform. A low friction type pneumatic cylinder with inner diameter of 9.3[mm], stroke of 100[mm] are used. The pressure in each cylinder and the displacement of piston are used for a feedback control. The controller generates control signals to drive control valves.

(a) Pneumatic parallel manipulator



(b) Wrist rehabilitation

Figure 15 Pneumatic rehabilitation device

The controller is constituted with an impedance control scheme using a disturbance observer. The impedance control is executed based on the measured force/moment applied by the patient. This study has shown that some typical exercise of *isometric*, *isotonic*, *passive isokinetic* and *active isokinetic* can be achieved by only adjusting the desired impedance parameters of stiffness and damping. A practical examination is next research subject to evaluate the availability of this rehabilitation machine.

WEARABLE POWER ASSIST DEVICE

It must be an earnest hope for the old aged or disable people to perform daily living activities as many as possible by themselves without the support of others. Further, their positive participant to the society is desired. It is also an important subject to relieve the physical burden of the care person. We have developed a wearable power assist device to cope with the above situation. A human wears the device. It supports various motions of the human by assisting the muscle power.

This device has to be a human friendly mechanism, which can be constructed with a pneumatic soft actuator. In Japan, some wearable power assist devices driven with pneumatic actuators have been developed. A power assisting suit by Yamamoto et al. is a pioneer study, driven with direct drive pneumatic actuators combining micro air pumps and pressure cuffs [6]. Kobayashi et al. have developed a muscle suit assisting a shoulder motion driven with McKibben type rubber muscles [7]. Tsukakoshi et al. have developed a new type pneumatic soft actuator named *wound tube actuator* and proposed a power assist device driven with this actuator for the limb motions [8].

We also have developed some types of wearable power assist devices driven with a different type of pneumatic soft actuator mentioned above.

Fundamental concept

Our fundamental concept in the development of a wearable power assist device is to use the most suitable type actuator for each part of human in order to make the structure as simple as possible.

Figure 16 shows a power assist device for elbow driven with a contracted curved type pneumatic rubber muscle shown in Figure 7. The rubber muscle is attached to the elbow through a supporter. The assist force can be controlled by adjusting the inner pressure of rubber muscle. Figure 17 shows a bending angles and an electromyogram (ENG) at biceps muscle of upper arm when the human bends an elbow holding a load mass of 2[kg] at the hand. The figure illustrates the effect of power assist. When the assist device works, the variation of electromyogram (CH2) is smaller than the case without power assist. The human can bend the elbow without own muscle power due to the power assist. The effect of power assist device is apparent.

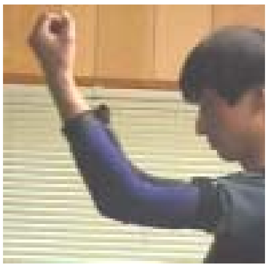


Figure 16 Power assist for elbow

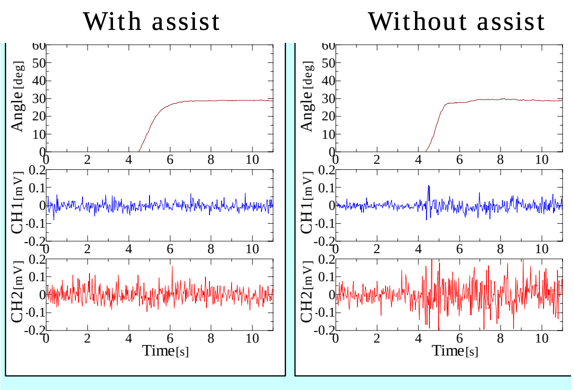


Figure 17 Effect of power assist

Figure 18 shows another example of a power assist device for shoulder part consisting of three McKibben type pneumatic rubber muscles. It assists a flexion of upper arm using two rubber muscles with length of 562[mm] and 793[mm] of which characteristics are shown in Figure 4. The adduction is assisted using the muscle with 408[mm] length.

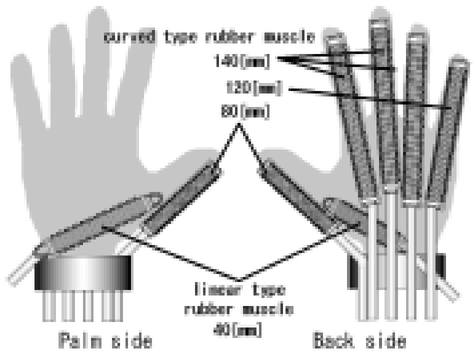
The power assist devices shown in Figure 16 and 18 are plot types of our research aimed as simple, lightweight and human friendly as possible wearable power assist device. Two examples are still primitive but available as a simple and easy power assist device.

Figure 18 Power assist for shoulder

POWER ASSIST GLOVE

We have developed a power assist glove for supporting activities of daily living, rehabilitation and various heavy tasks [9].

Figure 19 shows the structure and the outlook of developed power assist glove. It consists of the extended curved type pneumatic rubber muscles put on the backside of fingers, and the extended linear type muscles put on a root of thumb. When the human hand grasps the cylindrical bar with diameter 60[mm], the contact force at the finger tip is about 14 ~20[N]. Figure 10 shows that the enough generated force can be obtained from the glove.



(a) Structure

(b) Manufactured assist glove

Figure 19 Power assist glove

Figure 20 shows the various finger works possible with the glove. The movable range of the proposed power assist glove is enough for the required various finger works in the daily living. A proposed wearable power assist glove can be easily manufactured by attaching the pneumatic rubber muscles to a usual glove. The manufactured power assist glove is available to support the finger works required in daily living. Rehabilitation and various training may be additional effective applications of this glove.

(a) Tip pinch

(b) Side pinch

(c) Power grip

(d) Cylindrical grip

(e) Spherical grip

(f) Hook grip

Figure 20 Various finger works with glove

POWER ASSIST SPLINT FOR UPPER ARM

In the design of a wearable power assist device, a mechanical interface to transmit the generated force by actuator to the human body is important. Ideally the interface made of soft material such as supporter, band and glove shown in Figure 16, 18 and 19are desired for the comfortable equipment. However, where the large assist force is required, the combination with a suitable orthosis is considerable.

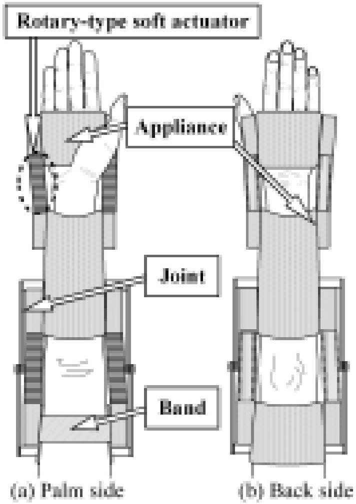
Structure

Figure 21shows the outlook and structure of the developed power assist splint, constructed with an orthosis made by forming a plastic used as a mechanical interface between actuators and human body. It assists the bending motions of wrist and elbow. Mechanical joints are equipped on both sides to restrict its movable range to the smaller than average maximum bending angles of Japanese male [10].

Actuator

A kind of extended curved type rubber muscle shown in Figure 9 is used as an actuator. A pair of the rubber muscles is attached to the wrist and elbow, respectively. Figure 22 shows the structure of rubber muscle manufactured for the elbow. It consists of a rubber tube and a polyester bellows. The outer and inner diameters are 20[mm] and 14[mm], the length is 290[mm]. The outer diameter of polyester bellows is 40[mm]. The bellows is reinforced with a fiber along the axial direction as shown in the figure. Owing to the

(a) Outlook



(b) Structure

Figure 21 Power assist splint

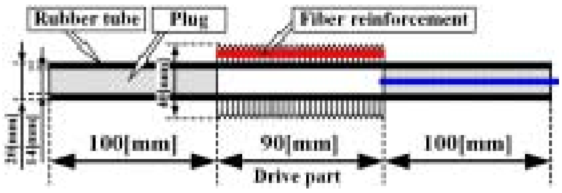


Figure 22 Structure of muscle for splint

reinforcement, when the compressed air is supplied into the actuator, only the other of reinforced side extends in the axial direction and produces a bending motion as shown in Figure 23.

Figure 24 shows the fundamental characteristics of actuator. The generated torque is measured for the constant inner pressure of 500[kPa]. It is confirmed that the generated torque is enough to keep the human forearm and palm having a load of about 4[kg] horizontally.

(a) Initial state

(b) Pressurized state

Figure 23 Outlook of muscle

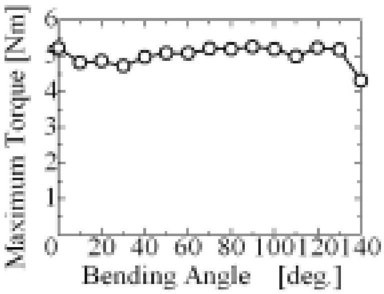


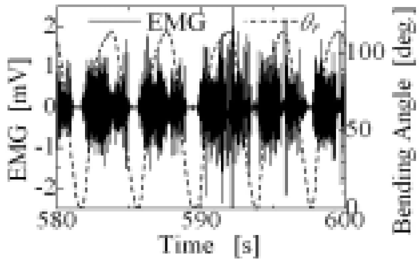
Figure 24 Generated torque of muscle

Effect of power assist

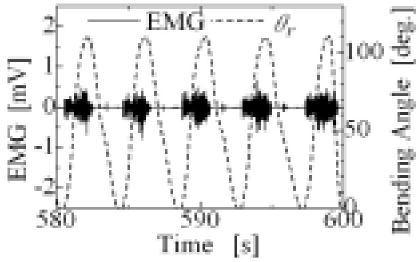
In order to verify the effect of power assist, a subject wearing the device bends his forearm repeatedly having a load of 3[kg] during 600[s]. The period of bending operation is 4[s]. Figure 25 shows the experimental results of bending angles and EMG. The difference of EMG owing to the existence of power assist confirms the effect of power assist. Further, when the power assist device doesn't work, the larger fatigue of muscle appears in the extension than the bending of forearm. When the device works, the fatigue of muscle is not recognized. The developed power assist splint is effective to assist the muscle power and to decrease the fatigue of muscle.

CONCLUSIONS

A human assist technology is essential in the highly aged society. A pneumatic power is effective to develop the human assist technology due to its inherent



(a) Without power assist



(b) With power assist

Figure 25 Effect of power assist

flexibility and human friendliness. A pneumatic soft actuator is applicable to construct various human assist devices. A pneumatic rubber artificial muscle is the typical pneumatic soft actuator. In this paper, four types of rubber muscles developed and manufactured in our laboratory are introduced. These muscles are available to constitute a human friendly soft mechanism and a wearable power assist device. The power assist device with a simple structure can be designed by using the suitable type of rubber muscle according to the property of assisted part of human body.

We have continued to establish a human assist technology based on soft mechanism, wearable power assist device and so on. A pneumatic power can be effectively used in this field. The collaboration among related technologies is expected for the innovation of fluid power technology.

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