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***Abstract*— In this study, in order to realize an assist of independent life for the elderly or people in need of care and relieve a physical burden for care worker, an active support splint driven by pneumatic soft actuator (ASSIST) has been developed. ASSIST consists of a plastic interface with the palm and arm and two rotary-type soft actuators put in both sides of appliance. In this paper, the fundamental characteristics of ASSIST is described, and then the effectiveness of this splint is experimentally discussed. Finally, the operation of ASSIST based on a human intention is described.**

***Index Terms*— Power Assist, Wearable Robot, Pneumatics, Artificial Rubber Muscle**

I. Introduction

In recent years, owing to a great advance of medical technology and a decrease of birth rate, a growth of advanced age society has become a serious problem in Japan. Therefore, it is becoming difficult to secure enough care workers for the elderly or people in need of care. In addition, relieving a physical burden of care work is important subject because it is hard physical work. In this case, if a slight symptom people in need of care is possible to have a daily life independently by some way, that way is one of effective means to solve the above problem about a care worker shortage. From above reasons, many kinds of power assist device have been developed [1,2,3]. The exoskeleton to assist a human upper-limb motion[1], the power-assisting device for the assist of self-transfer between a bed and a wheel chair[2] are floor type devices, they can realize effective assist according to the enough generated force. That is the strong point of both devices, but the movement in an arbitrary place is not supposed in these devices. To realize the movement in an arbitrary place for a user equipped with a device, a wearable type device has been adopted. Berkeley Exoskeleton [3] is one of wearable type devices. Berkeley Exoskeleton assists a lower limb motion by a pneumatic cylinder. However since the cylinder is constructed with rigid components, the cylinder lacks a flexibility except a moving direction. On the other hand, the soft actuator constructed with a soft material such as a rubber has an inherent flexibility besides a moving direction. It is the main advantage for the medical or the welfare application that the developed device has a flexibility due to not only the power source but also the body of actuator.

To assist people in need of care to be independent and relieve the burden on care workers, an active support splint driven by pneumatic soft actuator(ASSIST) for bending motion assist at a wrist has been developed. Since the mass and hardness of device involve the danger of causing a serious accident for the users or neighbors, this device is constructed with an appliance made by forming a plastic as an interface with human body, and by using a pneumatic soft actuator[7] which has a mechanical softness according to a material and a power source.

In this paper, the structure of developed power assist splint is described, and then the effectiveness of this device is experimentally discussed based on the experiments for the assisting both movable range and muscular endurance. Finally, the operation of ASSIST based on a human intention is described.

II. Structure of ASSIST

Fig.1 show the structure of ASSIST. In this study, two types of ASSISTs are developed. Fig.1(i) shows Type I of ASSIST is developed for realizing the assisting increase in movable range. Type II is developed for realizing the increase muscular endurance. The difference of both types is the existence of the McKibben type rubber muscle. The McKibben type pneumatic rubber muscles are attached for relieving a restrained feeling by releasing the palm appliance when the device is not operated.

Fig.2 shows the outlook of ASSIST. ASSIST is constructed with an appliance and two rotary-type soft actuators put in both sides of appliance. The width and length of splint are 150[mm] and 280[mm], respectively. The mass is 390[g]. Where a general baseball glove is compared with ASSIST as another device mounted to a hand, ASSIST is lighter than an baseball glove since the mass of glove is about 500!A600[g]. Therefore this splint is lightweight comparatively in devices mounted to a hand. In this section, the structure and fundamental characteristics of ASSIST are discussed.

Appliance

Fig.3 shows the appliance as an interface between a human body and the actuator. If the stiffness of appliance

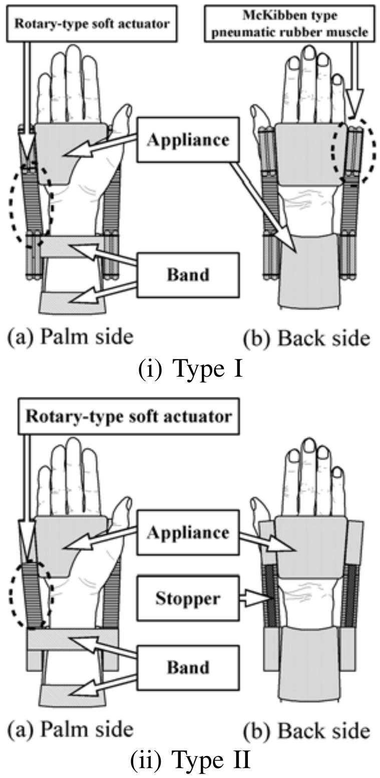


Fig. 1. Structure of ASSIST.

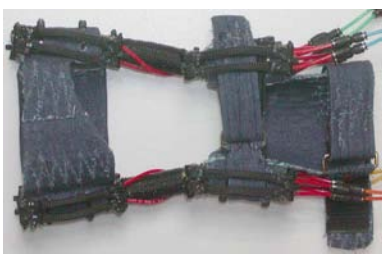


Fig. 2. Outlook of ASSIST.

is not enough, owing to the deformation of the palm with a complicated structure, and of a fixed part of actuator due to a high bending moment, it becomes difficult to transfer the generated torque from actuator to the human body efficiently. From the above, this appliance is made of a plastic same as the usual appliance. The shape of appliance is decided referring a shape of extension splint for a disabled person. Two cylindrical plastics are attached to the both sides of the palm and arm in order to fix the actuators.

Rotary-Type Soft Actuator

Fig.4 shows the structure of rotary-type soft actuator for type I. The rotary-type soft actuator consists of a rubber tube and two silicone rubber tubes, a polyester bellows. In order to bend circumferentially, the polyester bellows is reinforced with fiber as shown with the solid line in Fig.4(c). The both sides with length 50[mm] from the end are reinforced for inhibiting axial expansion. The bending side at center part of bellows with length 60[mm] is reinforced. Since the other side of the bellows expands to the

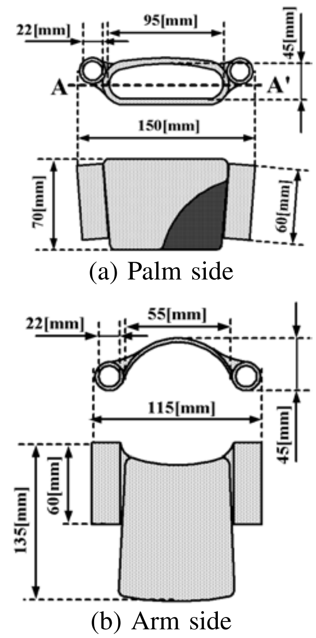
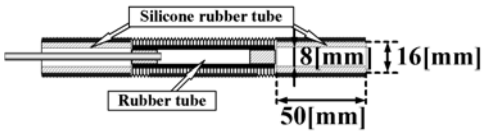


Fig. 3. Shape of appliance.

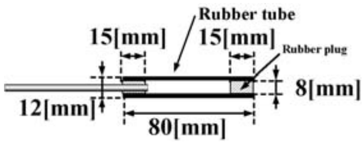
axial direction by reinforcement at the only bending side, this actuator bends circumferentially when the compressed air is supplied into the actuator. The part between the bending and fixed parts of the bellows is not reinforced for releasing the palm appliance. **Fig.5** shows the outlook of actuator. Depending on the reinforcement of bellows, when the compressed air is supplied to the actuator, the actuator expands to the axial direction as shown in Fig.5(b). **Fig.6** shows the size of the rotary-type soft actuator used for type II. The outer and inner diameter and length of rubber tube are 16, 12, 180[mm], respectively. The outer and inner diameter of polyester bellows are 28, 22, respectively The both sides of the bellows with length 60[mm] from the end are reinforced for inhibiting axial expansion. The bending side at center part of bellows with length 60[mm] is reinforced. **Fig.7** shows the fundamental characteristics of actuator. Enough bending angle $\delta\theta$ for assisting with human wrist can be obtained as shown in Fig.7(a). Fig.7(b) show the relation between a bending angle and a maximum generated torque with 500[kPa].

The mass of average Japanese male palm is about 560[g][4]. It supposes that the position of the center of gravity is the center of the palm[5], the required torque for support the palm is about 250[Nmm] per one actuator. The dashed line in the figure shows this required torque. From the result, an assisted bending angle of about 80[deg.] can be expected. The almost satisfactory bending angle can be obtained, since an average bending angle of a Japanese male is about 86[deg.][4,5].

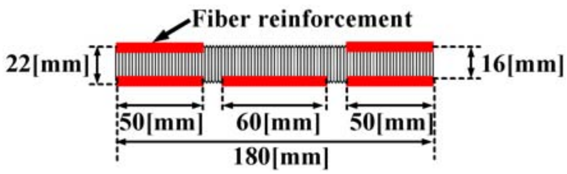
Fig.8 shows the torque characteristic of the actuator used for TypeII. To realize the assisting increase in muscular endurance, the required torque is more than type I. From the figure, the generated torque which is 5 times as much as one of actuator for type I can be obtained. For protecting the wrist, the stopper is attachd to the bending side for inhibiting the increase in the bending angle over 80[deg.].



(a) Rotary-type soft actuator



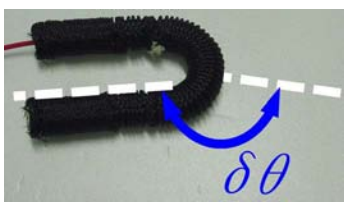
(b) Rubber tube



(c) Polyester bellows

Fig. 4. Structure of rotary-type soft actuator used for type I.


(a) Initial state



(b) Pressurized state

Fig. 5. Outlook of rotary-type soft actuator.

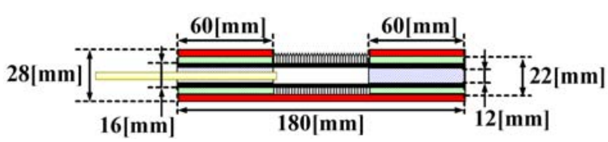
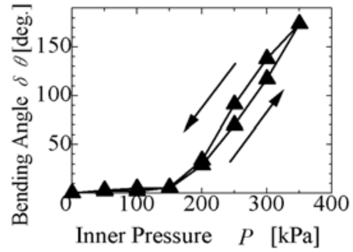


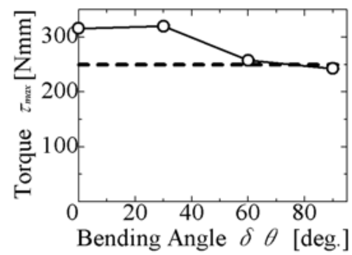
Fig. 6. Size of rotary-type soft actuator used for Type II.

Fundamental Characteristics of ASSIST

Fig.9 shows the generated torque of ASSIST. As compared with Fig.7(b),8, the torque which is twice as big as one of one actuator can be obtained. In contrast, the generated one with Type II decreases sharply with the increase in the bending angle. The decrease in the torque is caused principally by the deformation of the rotary-type soft actuator at the fixed part on the appliance. However, type II can apply the generated force of about 20[N] to the palm with keeping bending angle of 80[deg.]. **Fig.10** shows the pressure response of ASSIST. In addition, the angle responses of the actuator attached with ASSIST are also shown in this figure. The bending angles of both types saturate mechanically over 400[kPa], the dynamic characteristics is measured under 400[kPa] in this experiment.



(a) P-$\delta\theta$



(b) $\delta\theta$-τ_{max}

Fig. 7. Fundamental characterisics of actuator.

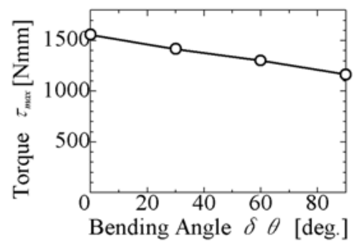


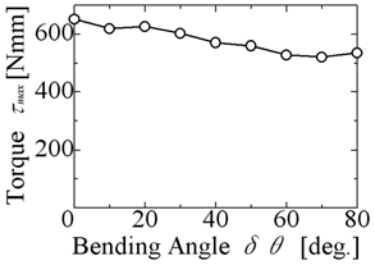
Fig. 8. Torque characterisic of actuator used for typeII.

From the figures, although the increase of the angle is small in the lower pressure region under 200[kPa] due to the non-linear characteristic of the actuator, the delay to the pressure do not appear in the high pressure region.

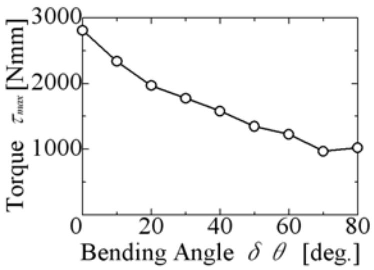
III. Increase in Movable Range

In this section, an effectiveness of the assisting increase in movable range for a muscularly weak human is discussed experimentally.

Fig.11 shows the assisting scene. In this experiment, a human wrist is bended by ASSIST without a human muscular force. For evaluating the assist effectiveness, the bending angle at human wrist is measured. In addition, EMG is measured in order to confirm the muscular power from human. The wrist operates stepwise and sinusoidally both cases with and without the splint. EMG is measured at a flexor carpi ulnaris as shown in **Fig.12**. A flexor carpi ulnaris is one of muscles for bending a wrist[6], therefore

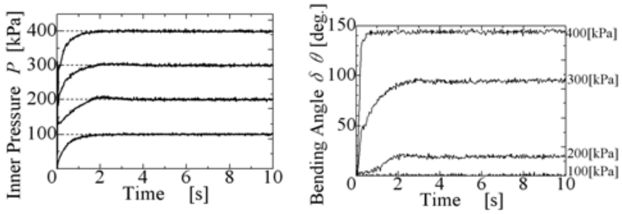


(a) Type I

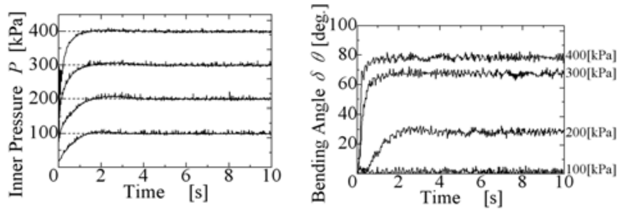


(b) Type II

Fig. 9. Relation between $\delta\theta$ and τ_{max}.



(a) Type I

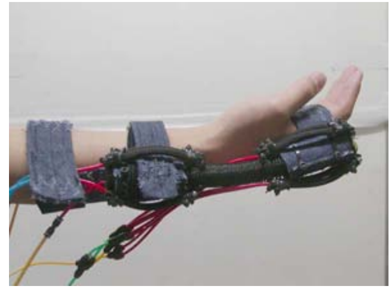


(b) Type II

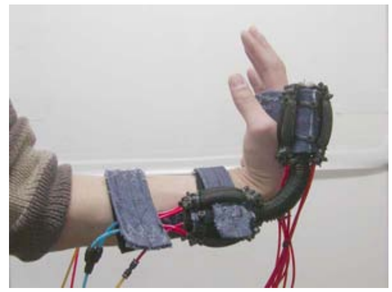
Fig. 10. Relation between t and P,$\delta\theta$.

it is selected as a measured point of EMG. ASSIST is controlled by the pressure control system.

Fig.13 shows the experimental results with and without ASSIST when the wrist is bended stepwise. The bending angle without assist is about 86[deg.]. This value is roughly equivalent to an average bending angle of Japanese male. The bending angle with the assist is about 80[deg.]. The almost satisfactory bending angle can be obtained. The large difference in the amplitude of EMG can be confirmed in the cases with and without ASSIST. Since the amplitude of EMG with ASSIST decreases compared with the amplitude without one, the burden for the muscle can be decreased by the generated torque from ASSIST. **Fig.14** shows the experimental results with and without ASSIST when the wrist is bended sinusoidally. The generated torque from ASSIST can also decrease the burden at muscle. By using ASSIST, the bending motion can be realized even when a human does not generate a muscular force.



(a) Initial state



(b) Pressurized state

Fig. 11. Assisting scene

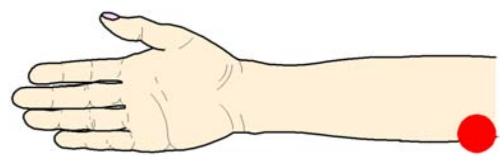


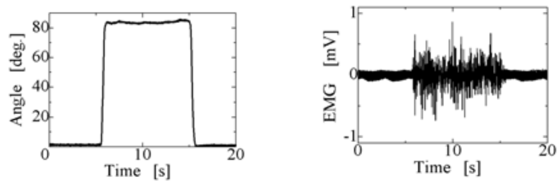
Fig. 12. Measured point for EMG.

IV. Increase in Muscular Endurance

For evaluating the effectiveness of muscular endurance assist quantitatively, the method of Mosso's ergograph known as one of method to measure muscular fatigue is applied to this experiment. In the method of Mosso's ergograph, a periodical motion of the measured body part is repeated under the applied load, and the changing amplitude of displacement with time is measured.

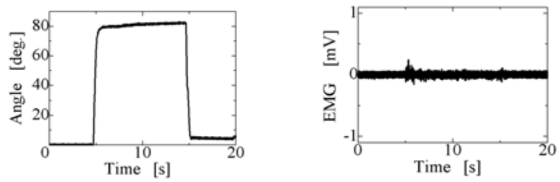
In this experiment, the angles at the wrist are measured with and without ASSIST Type II as shown in **Fig.15**, and the load is 3[kg], the period of bending motion is 2[s], the experimental time is 400[s].

The subjects are 5 Japanese males. **Fig.16** shows two results as the examples of the large and the small effect . In the case of the experiment without ASSIST, the bending angle decreases steeply or the magnitude of bending angle varies widely according to the muscular fatigue. In the case of using ASSIST, although the bending angle also decreases, the decreased angle is smaller than the decreased one without ASSIST. In addition, though the tendencies of both results in the case without ASSIST are different quite each other, the difference of the tendency becomes small by using ASSIST. From these results, ASSIST is



(a-1) Angle (a-2) EMG

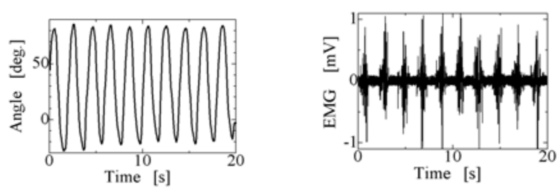
(a) Without ASSIST



(b-1) Angle (b-2) EMG

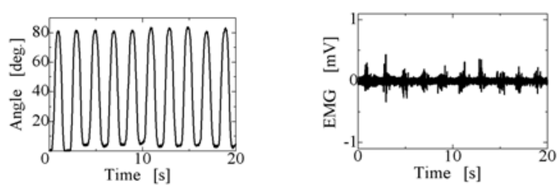
(b) With ASSIST

Fig. 13. Experimental results (Step motion).



(a-1) Angle (a-2) EMG

(a) Without ASSIST



(b-1) Angle (b-2) EMG

(b) With ASSIST

Fig. 14. Experimental results (Sinusoidal motion).

effective to decrease not only the muscular fatigue but also the difference among the human capability.

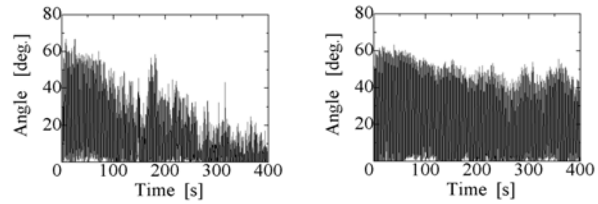
V. Operation Based on a Human Intention

From the above experiments, the effectiveness of ASSIST is verified experimentally through the assisting increase in movable range and muscular endurance. In order to operate ASSIST based on a human intention, the input device for ASSIST must be developed. For realizing the simple structure and operation of ASSIST, it is desirable that also the input device has a simple structure. Then the bend sensor which the resistance is increased with increase in the bending angle is equipped to the side of appliance, the inner pressure of the rotary-type soft actuator is determined from the change of bending angle of ASSIST according to the increase or decrease in the bending angle of the human wrist. The outlook and characteristic of the bend sensor are shown in **Fig.17**. As one of control method of the inner pressure based on the bending angle, ASSIST

(a)Without ASSIST

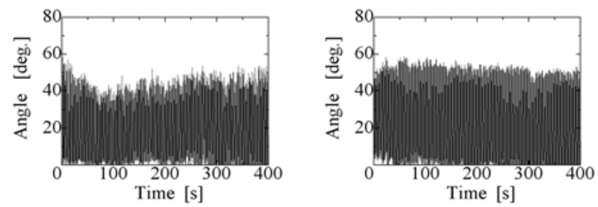
(b)With ASSIST

Fig. 15. Shene of muscular endurance assist



Without ASSIST With ASSIST

(a) Subject A



Without ASSIST With ASSIST

(b) Subject B

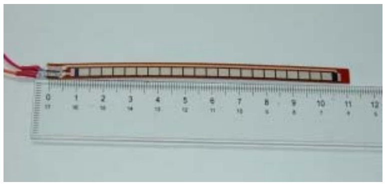
Fig. 16. Experimental results

is switched ON or OFF using a threshold determined from the absolute bending angle of wrist. However, since a movable range differs in every human, different threshold values must be determined. In this study, by using the moving average of bending angle of ASSIST, the inner pressure is switched as follows and shown in **Fig.18** when the difference of the measured angle and the moving average one becomes over or under the threshold.

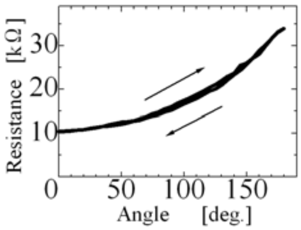
$$
\begin{aligned}
P &= P_{max} \quad (\theta - \theta_a \geq \theta_t) \\
P &= 0 \quad (\theta - \theta_a \leq -\theta_t)
\end{aligned}
$$

$\theta, \theta_a, \theta_t$ represent the measured angle, the moving average one and the threshold, respectively. The moving average time is 1[s], and θ_t is 5[deg.]. **Fig.19** shows the experimental result. In this experiment, the wrist with ASSIST is bended with frequency of 0.5[Hz], and the bending angle of wrist and EMG at a flexor carpi ulnaris are measured.

As can be seen in the figures, ASSIST can be switched ON or OFF when the human bends or extends the wrist under the condition of keeping the inner pressure of the actuator constant. It can be verified from the EMG signal that the muscular power is hardly required even when the human intends to bend his wrist. From the results, ASSIST can operate based on a human intention.



(a) Outlook



(b) Characteristic

Fig. 17. Bend sensor.

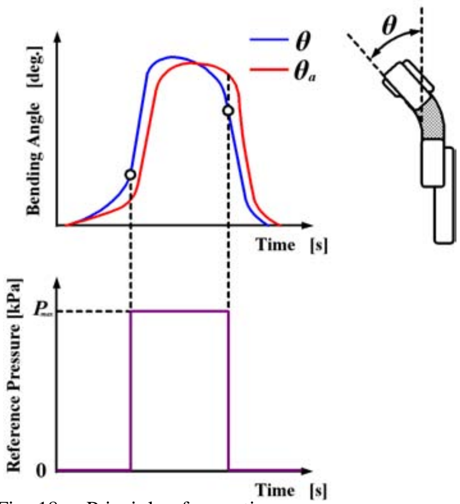
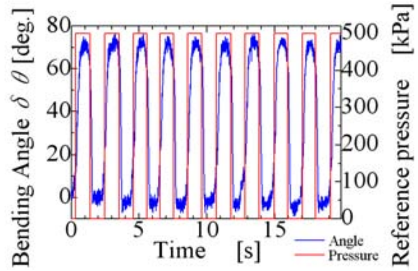
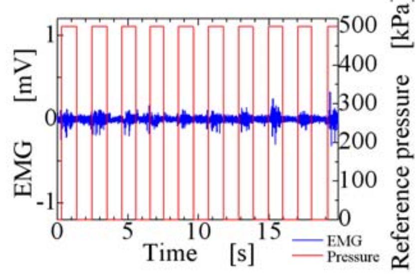


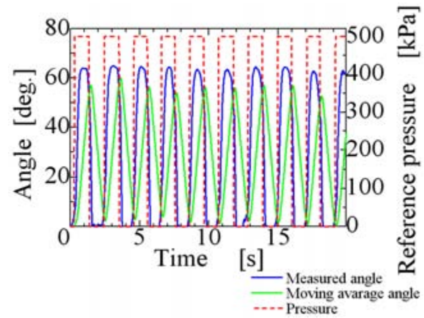
Fig. 18. Principle of operation.



(a) Angle (Wrist)



(b) EMG



(c) Angle (ASSIST)

Fig. 19. Experimental results.

VI. Conclusion

In this paper, the structure and the fundamental characteristics of ASSIST have been described, and then the effectiveness of ASSIST has been verified experimentally through the assisting both movable range and the muscular endurance. The main results and the future works of this study can be summarized as follows:

1) The bending angles at the stepwise motion without and with ASSIST are about 86, 80[deg.], respectively. The almost satisfactory bending angle can be obtained with ASSIST in the condition that the human generate no muscular power.
2) There is the large difference in the amplitudes of EMG at stepwise and sinusoidal motions with and without ASSIST. Therefore, it can be proved that ASSIST can be realized an bending motion even without a human muscular power. In addition, the fact (1) has been proved from EMG signal.
3) ASSIST is effective to decrease not only the muscular fatigue but also the difference among the human capability.
4) By using a bend sensor, the operation based on a human intention can be realized. To realize the complicated motion and the control method are the future works.
5) The power source of ASSIST is supplied from the external compressor. To improve the wearability, the miniaturization of the compressor is the future work.

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