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Performance evaluations of hand and forearm support system

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Abstract— **This paper reports support effects of an exoskeleton system for activities of a hand and an upper limb of a healthy person. The support system augments human forces of a hand, a wrist joint and an elbow joint based on bioelectric potential of each muscle so that the upper limb could be assisted by the exoskeleton with a certain rate of wearer's force. Actuators in the assistive system are replaced with powerful ones to supports human hand, wrist and elbow activities with larger force and torque. Through experiments it was confirmed that a wearer receives physical support from the system for activities of a hand, a wrist and an elbow joint and then we evaluate rate of assistance by comparing the magnitude of the bioelectric potential between under a supported phase and under an unsupported phase.**

I. Introduction

Japan is facing a challenge with regard to the aging society with low fertility rate and the rapidly growing rate of elderly people. It is estimated that the ratio of old population (more than 65 years old) to total population will be 40.5% in 2055[1]. The elderly people often feel inconvenience in the daily life due to the depression of musculoskeletal system and sensing system. As a result, the number of people who need care will increase in aging society. As one of solutions for sustainable aged society, healthy old people are expected to assist other old people who need support in daily life. It is heavy task even for a healthy young person to help old people who cannot stand up by himself in transferring from a bed to a wheelchair. That is why a lot of exoskeleton systems are developed to support a healthy person [2], [3] and a physically challenged person [4], [5].

There are some exoskeleton assistive systems that augment a grasping force and wrist joint torque of human [6], [7],[8]. However they restrain thumb and wrist activities and then some degrees of freedom of a wearer's hand and wrist are lost. Besides a link-drive mechanism with pneumatic actuators needs relatively large space for a cylinder, an air compressor and an accumulator. As a result, it deteriorates its utility.

Generally, dexterous tasks are charged for an upper limb in a daily life, because some tasks require precise position control of fingertips and some tasks require precise force control at fingertips. For example, a pick and place behavior with a small object requires both precise controls. In order to support activities of an upper limb of a healthy person, the supports system should not disturb the dexterous motion.

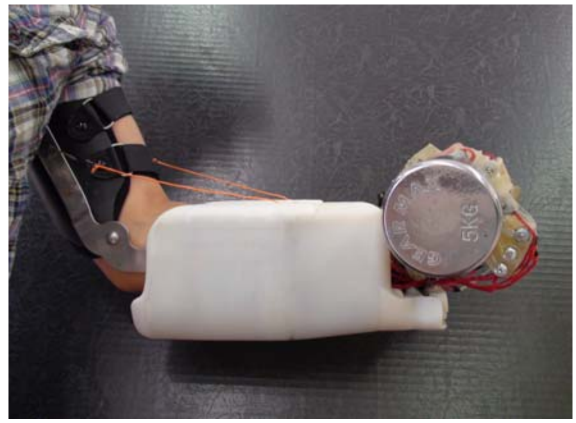

Fig. 1. Hand and forearm support system. A computer running real-time OS, motor drivers and six motors are embedded into a forearm part. Eight motors are embedded into a hand part. Only battery is not included in this figure. Total weight is about 2000[g].

On the other hand, the system should support a wearer's motion that needs large force such as a heavy object lifting action. A bioelectric potential-based switching control and a tendon-driven mechanism with DC motor satisfy these two requirements for the upper limb support. In the following mode of the switching control, the DC motor is controlled for an exoskeleton to follow a human activity, while the DC motors assist human activities with a support force that is proportional to the human force in a torque assistance mode of the switching control.

This paper first explains an exoskeleton support system whose actuator system is updated based on the previously developed support system [9]. This paper then reports performances of the updated system in which the bioelectric potential-based switching control algorithm is installed so that the system could augment force or torque of human more strongly if necessary, and so that the system could synchronize human upper limb's activities without any contacting force sensor between a forearm and the exoskeleton system.

The rest part is organized as follows. In section 2, the system structure and drive mechanisms are explained and then the bioelectric potential-based switching control algorithm is explained in section 3. Performance of the developed system is investigated in section 4.

II. System components

This section introduces the mechanisms of the assistive system for the hand, a wrist joint and an elbow joint (Fig.1). This system consists of a hand part, a forearm part, and an upper arm part. The hand part has eight motors for finger

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assistance and the forearm part has a controller for a whole system, six motors for wrist and elbow assistance, motor drivers, and a communication device inside.

A. Drive mechanism for finger joint

We propose poly-articular tendon drive mechanism to simulate variable compliance of a human finger with simple mechanism. Three tendons shown in Fig. 2 are used and they are pulled by three DC motors independently. A direction of a grasping force at a fingertip can be controlled and a potentiometer is embedded at each finger joint to measure finger joint angle.

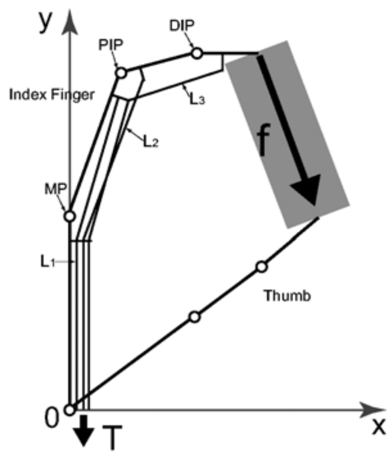

Fig. 2. Tendon-driven mechanism for index finger

The index finger is driven by the poly-articular tendon drive mechanism with three DC motors. The middle finger, the ring finger and the little finger are coupled and driven by the other poly-articular tendon drive mechanism with three DC motors. These six DC motors are mounted on wearer's backhand, separating into two drive parts: three motors for an index finger and three motors for the three coupled fingers. The two drive parts are connected by a universal joint that allows fingers to adduct and abduct and allows a palm to deform for finger opposition. The specification of the motors for each tendon is listed on Table I.

TABLE I
DC MOTORS USED TO DRIVE EACH TENDON OF THE HAND PART.

	L_1 and L_2	L_3
Motor	FAULHABER 1524T006SR	MAXON RE10 0.75W
Initial torque	6.68mNm	1.25mNm
Gear ratio	76:1	64:1
Diameter of pully	7.5mm	7.5mm

A thumb is also assisted by exoskeleton with two motors, two wires and two links (Fig.3). Flex and opposition of the thumb are indispensable to grasp various-shaped object at arbitrary posture. The thumb's flexion is supported by using a $wire2$ and the thumb's opposition is supported by using a $link1$, a $link2$ and a $wire1$. The $link1$ transmits the torque of a $motor$ embedded in the exoskeleton, The $link2$ binds the MP joint of a thumb on the circular path and the $wire1$ is strung parallel with the opponens pollicis muscle and the flexor pollicis brevis that are the agonist muscle of the thumb's opposition, then the $wire1$ is driven by the other $motor$.

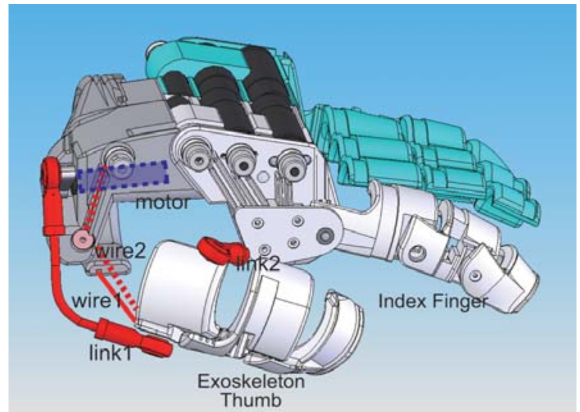

Fig. 3. Enlarged detail around thumb

B. Drive mechanism for wrist joint

A wrist joint is driven by a tendon drive mechanism as well as the finger joint. Four wrist motions: flexion, extension, pronation, and supination are supported by four wires and four DC motors (Fig.4). The wires that connect a finger part are actuated by DC motors: a motor(A) supports pronation, a motor(B) supports supination, a motort(C) supports flexion and a motor(D) supports extension. This wrist joint becomes passive for two remaining motions: ulnar flexion and radial flexion, therefore it has all DOF of human wrist joint. The work angles of wrist joint are listed on Table II and the specification of the motors for each tendon is listed on Table III.

TABLE II
WORK ANGLES OF WRIST JOINT OF HUMAN AND SUPPORT SYSTEM

	Flexion	Extension	Supination	Pronation
Support system	45°	65°	90°	90°
Human wrist	70°	90°	90°	90°

TABLE III
THE SPECIFICATION OF THE MOTORS FOR WRIST JOINT SUPPORT.

	Pronation,Supination	Flexion,Extension
Motor	FAULHABER 1724T006SR	FAULHABER 1724T006SR
Initial torque	11.5mNm	11.5mNm
Gear ratio	159:1	159:1
Diameter of pully	7.5mm	7.5mm

The drive mechanism for wrist joint has a tensioner that consists of a $Potentiometer$, a $TorsionCoilSpring$ and a

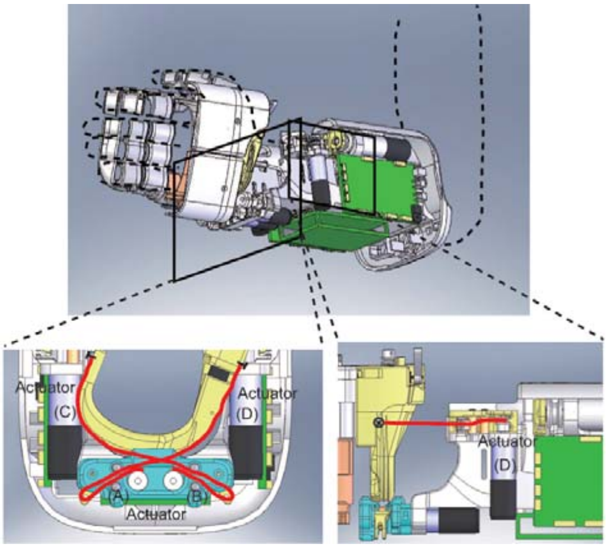

Fig. 4. Drive mechanism for wrist joint

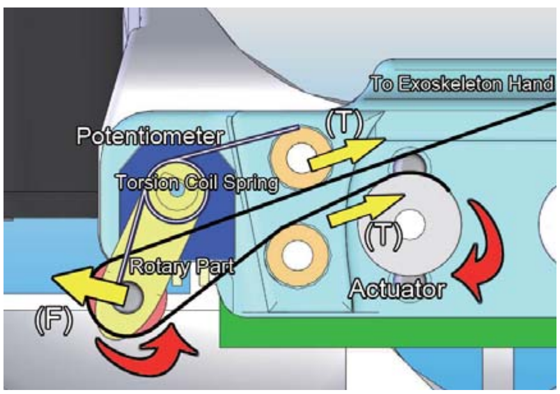

Fig. 5. Mechanism of tensioner

RotaryPart for each motor (Fig.5). The *RotaryPart* is rotated by the resultant force that consist of the tension of the wire (T) and the force of the *TorsionCoilSpring* (F). The angle of the *RotaryPart* is measured by the *Potentiometer*. This information of the angle is used in the wrist following control that synchronizes human motions and system motions.

C. Drive mechanism for elbow joint

A flexion of an elbow joint is assisted by two wires actuated by two motors and the elbow joint is not actuated in an extension direction. The detail view is shown in Fig.6 and the specification of the motors is listed on Table IV. We set out the mechanism that flexes the elbow joint with 5kg weight by itself when the motors are actuated at a power supply of six [V].

D. Active electrode for bioelectric potential

A bioelectric potential is measured by surface muscle electrodes for grasping force estimation and torque estimation of the wrist and the elbow joint. Our developed active electrode is attached along the corresponding muscles through two Ag/AgCl gel sheets. The active electrode includes an

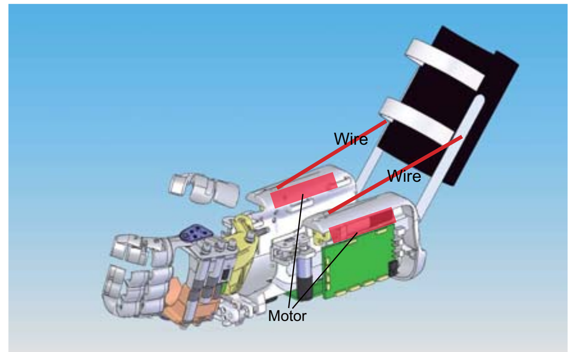

Fig. 6. Mechanism of elbow joint

TABLE IV
THE SPECIFICATION OF THE MOTORS FOR THE DRIVE MECHANISM FOR ELBOW JOINT.

Motor	FAULHABER 2232T012SR
Initial torque	46.8mNm
Gear ratio	66:1
Diameter of pully	14mm

impedance transfer for artifact reduction, amplifier ($\times$5000 - 20000). This active electrode is 25mm long, 34mm wide, 8.5mm high and 6g.

III. BIOELETRIC POTENTIAL-BASED SWITCHING CONTROL

Human hand has very wide range of generating force from small and precise force control such as pinching a small and lightweight object to large force control such as grasping a heavy object. It is reasonable that it supports grasping force only when force support is necessary for a hard work and that it almost vanishes so as not to disturb human hand activity during its precise manipulation. The same is equally true for the wrist.

We proposed a bioelectric potential-based switching control that switches two control modes: a following control mode and a torque assistance control mode [9]. The torque assistance control works only when an integral value of bioelectric potential exceeds a threshold. The integral value of a bioelectric potential "IBEP" is calculated by

$$IBEP(t) = \int_{t-T}^{t} bep(i)di, \tag{1}$$

where t is time, T is an accumulation period and $bep(i)$ is the electric potential measured at time i. The finger-following control is activated in the rest time. The block diagram is shown in Fig. 7.

A. Control for finger joints

1) Following control: It can flex and extend freely if the DC motor rotates so as to keep the wire slightly relaxing. The finger-following control enables a human finger to be free from DC motors by controlling the DC motors.

The control algorithm is as follows; The corresponding wire length L_i to the current joint angle θ_i is calculated by

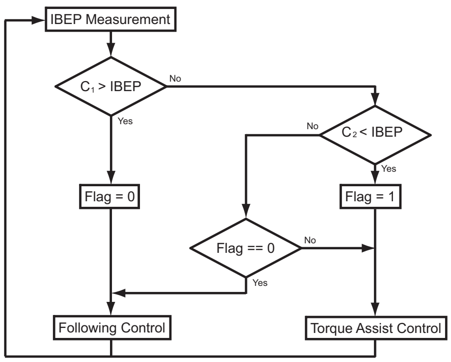

Fig. 7. Bioelectric potential-based switching control. The thresholds C_1 and C_2 are empirically determined based on a signal gain and a noise level.

using inverse kinematics. A target angle of a DC motor P_i is also calculated by using diameter of a pulley and an initial wire length L_{0i}. The block diagram is shown in Fig. 8.

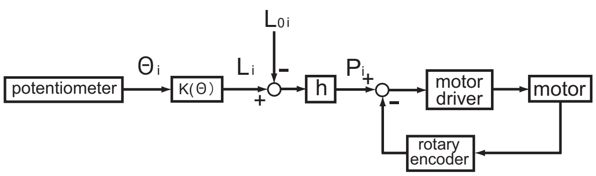

Fig. 8. Block diagram for finger-following control

2) Force assistance control: The direction of grasping force assisted by the exoskeleton is determined according to the relative position with an index fingertip and tip of a thumb. A magnitude of a grasping force assisted by the exoskeleton is a certain rate of the human grasping force that is estimated by the IBEP of lumbrical for the index finger and the IBEP of flexor digiti minimi brevis muscle for the three coupled fingers. Each motor torque required for the desired assistive force is calculated by Jacobian matrix.

B. Control for wrist joint

1) Following control: To synchronize the system motion with the human motion, we propose an algorithm that controls the DC motor to keep the wire's tension constantly low using the current angle of the tensioner. Therefore, it keeps the angle of a *RotaryPart* in the tensioner constant. For example, when the wire is too slack, the system controls the DC motor to roll up the wire. On the other hand, when the wire stretches too tight, the system controls the DC motor to relax the wire.

2) Torque assistance control: In the torque assistance control, we use a pronator teres for pronation, a flexor carpi radialis for flexion, an extensor carpi radialis for extension and a lumblical and a flexor digiti minimi brevis muscle for supination. A magnitude of an assistive torque is a certain rate of the human torque that is estimated by the IBEP of each muscle. In a case of supination, this system assists the motion if the IBEP of lumbrical does not exceed a threshold and the IBEP of flexor digiti minimi brevis muscle exceeds a threshold, and the magnitude of an assistive torque is determined by the IBEP of flexor digiti minimi brevis muscle.

C. Control for elbow joint

The magnitude of an assistive torque is determined by the IBEP of biceps. If the IBEP is under threshold, the system does not assist human elbow and become a passive joint.

IV. Experiments

We confirm the performances of the developed system through preliminary experiments with a subject who is a 24 year-old man.

A. Assistive force of hand part

We confirm the performances of the hand part through two experiments. One of the experiments is that the assistive system with a human phantom lifts the weight as heavy as possible as shown in Fig.9 As a result of the experiment, the system lifted the about 5.5kg weight.

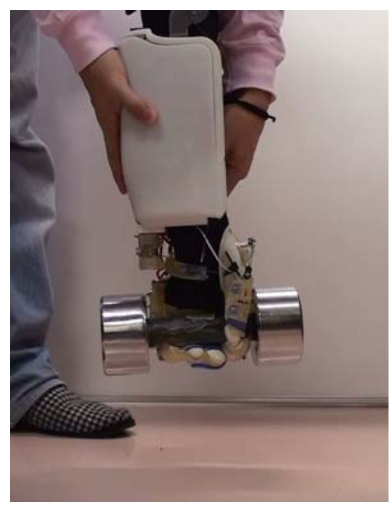

Fig. 9. The system holds up five-kilogram weights.

In the other experiment, human wears the assistive system and grasps the hand griper to keep a certain displacement as shown in Fig.10. The system first supports grasping force of a human for four seconds and then the system stops supporting, but a wearer tries to keep the displacement by compensating the system assistance by himself. The bep of lumbrical is measure at that time and then the IBEP is calculated by using eq.(1)

A mean IBEP of lumbrical in five iterations is shown in Fig.11. The IBEP of lumbrical is increased about 15.3% when the assistance is interrupted. The wearer tried to keep the displacement by increasing his grasping force up to about 18kg in this case. As a result, the wearer is assisted about 2.7kg grasping force.

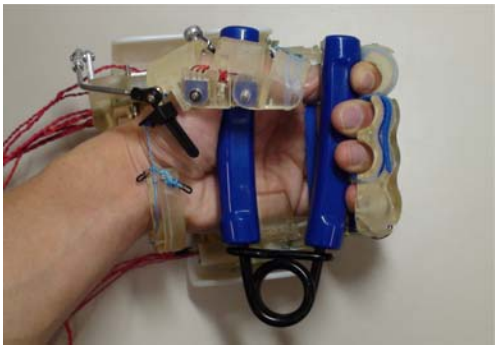

Fig. 10. Grasping the handgripper and sensing the integration of bioelectric potential

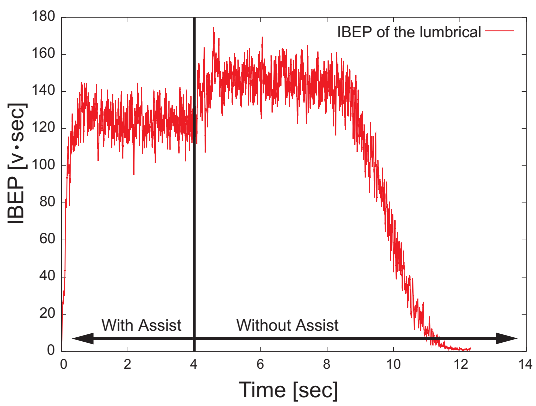

Fig. 11. Integration of bioelectric potential (lumbrical)

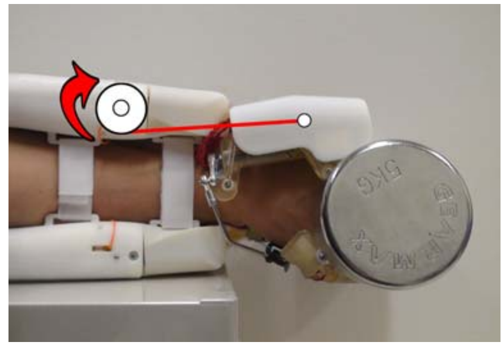

Fig. 12. Keeping the wrist angle constant(dorsal extenstion)

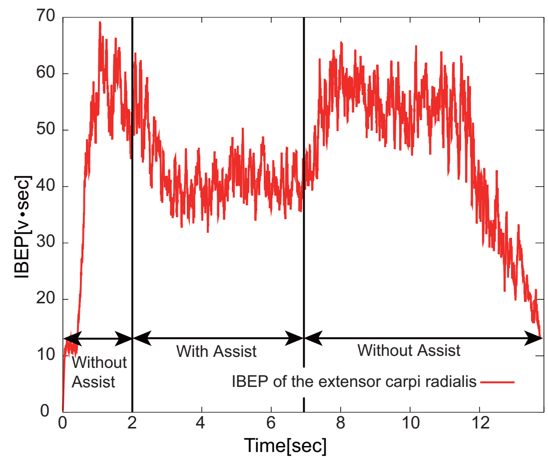

Fig. 13. Integration of bioelectric potential (extensor carpi radialis)

B. Assistive torque of wrist joint

We confirm the performances of the wrist part of the assistive system through two experiments for dorsal extension and pronation.

A subject with the assistive system tries to keep the angle of wrist joint constant while grasping a 5kg weight as shown in Fig.12. In this case, the system supports a wearer's wrist for five seconds after two seconds from beginning and then the system stops supporting. In this experiment, the wearer's fingers are not assisted. The load about 4400mNm affects on the human wrist since a distance between the 5kg weight and a wrist joint is 0.09m.

The mean IBEP of an extensor carpi radialis in five iterations is shown in Fig.13. The figure shows that the IBEP was decreased about 24.9% by the assistance. In fact, this rate of decrease means that the wearer's wrist is equivalent to about 1100mNm. As a result, the wearer felt as if the weight were about 3.75kg.

In the experiment for pronation, we use a stick whose weight is 0.2kg and that strings out a 1kg weight at distance of 0.25m from the human hand. Then a human grasps this stick and keeps it horizontal as shown in Fig.14.

In the experiment for pronation, the load from the stick and the weight was about 2700mNm and it was on the human wrist. A mean IBEP of pronator teres in five iterations is shown in Fig.15. The figure shows that the IBEP was decreased about 36.6% by the assistance. In fact, this rate of decrease is equivalent to about 990mNm. As a result, the wearer felt as if the weight strung out were about 0.6kg.

C. Elbow part

A human wearing the system grasps a 8kg weight with his hand and keeps the elbow joint flexed as shown in Fig.16. The elbow's position is fixed by the knee joint like a posture of concentration curl exercise. The torque about 23500mNm affects on the human elbow since the distance from elbow joint to the weight is 0.3m.

The system supports a wearer's elbow joint torque for eight seconds from the beginning, and then the system stops supporting. We set rate of the assistance 50%. In this experiment, the wearer's fingers and wrist joint are not assisted.

A mean IBEP of biceps in five iterations is shown in Fig.17. A mean IBEP is increased for compasation when a subject lifts a 4kg weight by himself. The mean IBEP with the assistance was about 102 [v·sec] and without assistance was about 187 [v·sec]. The load and BEP have a linear relationship. As a result this results means that the wearer's elbow was assisted about 10,700mNm and the wearer felt the weight about 3.6kg, while the mean IBEP during lifting the 4kg weight without any assistance was about 95. It is almost equivalent to the mean IBEP with assistance when lifting the 8kg weight. A rate of the assistance is about 50%

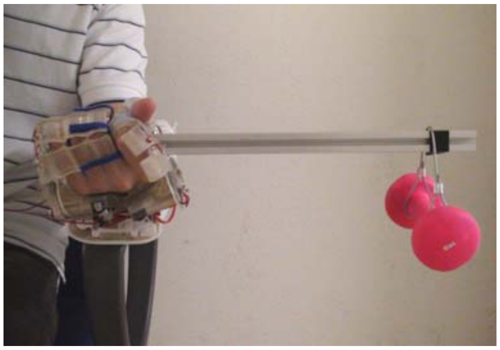

Fig. 14. Keeping the wrist angle constant(pronation)

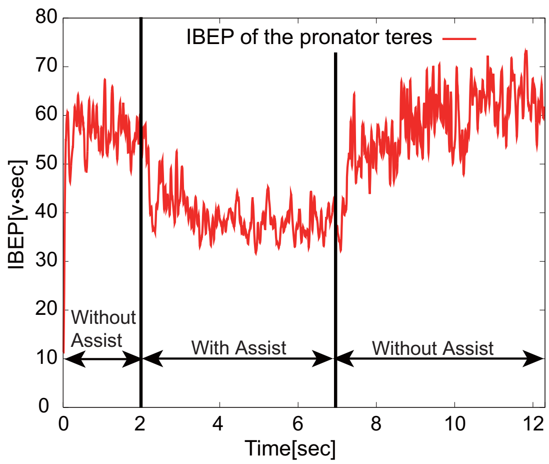

Fig. 15. Integration of bioelectric potential (pronator teres)

Fig. 16. Keeping the elbow angle constant

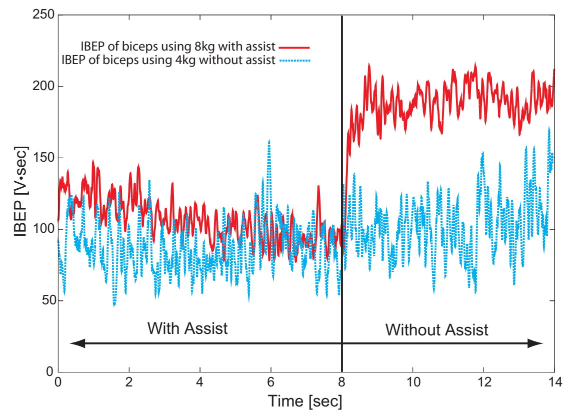

Fig. 17. Integration of bioelectric potential (biceps)

that is the same as one we designed.

V. Conclusions

This paper explained the exoskeleton support system for activities of an upper limb and a hand. Actuators in the assistive system are replaced with powerful ones to supports human hand, wrist and elbow activities with larger force and torque. A wearer's upper limb received physical support from the assistive system only when a wearer needs a larger force. As a result, the total system did not disturb dexterous activities of human upper limb. Through experiments it was confirmed that a wearer received physical support from the system for hand, wrist and elbow activities and then we evaluated rate of assistance by comparing the magnitude of the bioelectric potential between under the supported phase and under the unsupported phase.

VI. Acknowledgments

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