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Five-Fingered Assistive Hand with Mechanical Compliance of Human Finger

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Abstract— **This paper introduces an exoskeleton assistive hand that supports human hand and wrist activities by using user's bioelectric potential to control the exoskeleton movement. The exoskeleton has three active joints for an index finger, three active joints for combination of a middle finger, a ring finger and a little finger and two active joints for a thumb. It also has two passive joints between the index finger part and the combined part of the three fingers. Our proposed poly-articular tendon drive mechanism simulates a mechanical compliance of a human finger so that the exoskeleton could realize comfortable and stable grasping. This paper proposes a new mechanism "dual sensing system" and a new control algorithm "bioelectric potential-based switching control" so that the exoskeleton could synchronize wearer's hand activities without any force sensor. A tendon-driven mechanism and a dual sensing system enable wearer's fingers to move freely when they does need power assist but precise position control or force control. A bioelectric potential-based switching control enables the exoskeleton to augment their grasping force only when wearer's fingers generate a relatively large grasping force. A five-parallel-link mechanism is used to assist wrist activities of a wearer. Through experiments it is confirmed that the exoskeleton does not disturb a wear's pinch of a small object and that it augments grasping force for a heavy work.**

I. INTRODUCTION

Force and moment balance is indispensable for stable grasping and then compliance of fingertip becomes important for stability when the grasping points is not fixed in advance due to unknown shape of a target object. The compliance in direction of the grasping force is important in this case In addition the compliances in the orthogonal direction to the grasping force are sometimes important. The compliance of human fingertip mechanically changes according to the grasping force. For example fingertip compliance becomes small when the fingertip generates large grasping force. We therefore change a grasping force as well as grasping positions in order to adjust peg's compliance when we insert the peg into a pole. Compliance control of fingertip is one of requirements for dexterous manipulation.

Human finger has an intrinsic character about variable compliance explained above and then some research is reported to simulate the variable compliance. An electrical compliance control has been reported, however it needs a force sensor and it cannot respond to an impulsive force such as a collision force. On the other hand, mechanical compliance[1]–[3] is focused on due to its simplicity and performance: no sensor and quick response. Programmable Passive Impedance (PPI) [1] is a pioneer research that uses antagonistic pair of nonlinear springs for variable compliance. However they use two nonlinear springs and tendons simultaneously while human uses one side of them for grasping. Therefore we propose a new tendon driven system that can simulate variable compliance of a human fingertip using poly-articular tendon driven system.

Fig. 1. Five-fingered assistive hand on forearm

There are some exoskeleton powered hand that provides power augmentation for hand and wrist activities of a human[4] [5]. However they are supposed to restrain thumb and wrist activities and then some degrees of freedom of a wearer's hand are lost. Besides a link-drive mechanism with pneumatic actuators needs relatively large space for a cylinder and an air compressor or an accumulator. As a result, it deteriorates its utilities. On the contrary, some tasks require precise position control of fingertip and some tasks require precise force control at fingertip. Generally, an assistive hand should assist a grasping force of human finger only when a relative large grasping force is necessary. Besides, the system must not disturb hand activity when a precise position control or a precise force control is required.

We therefore propose a dual sensing system and bioelectric potential-based switching control algorithm so that the system could provide grasping force if necessary, and so that the system could synchronize human finger activities without any contacting force sensor between a finger and the exoskeleton system. The rest part is organized as follows. In section 2, the system structure and mechanism is explained and then the control algorithm is explained in section 3. Performance

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of the developed system is investigated in section 4.

II. EXOSKELETON ASSISTIVE HAND

This section introduces an exoskeleton assistive hand (Figs.1 and 2) that augment a grasping force of an index finger, the combined three fingers and of a thumb as well as wrist joint torques. This system has been developed to have four advanced features for grasping force support as follows,

1) The system supports grasping force that is proportional to a human grasping force. The human grasping force is estimated by measured bioelectric potential.
2) The system does not disturb human finger motion by synchronizing human finger motion when power support is not necessary so that human finger could move as if it wore nothing on it.
3) The assistive system simulates variable compliance of a human finger so that grasping stability and dexterity could be conserved.
4) Wrist joint torque is also assisted by a parallel link mechanism.

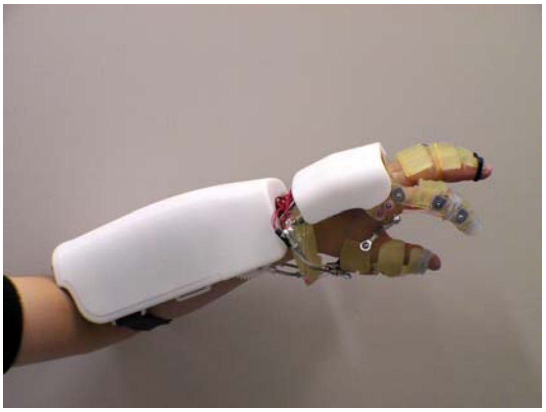

Fig. 2. System components: a system controller on wearer's forearm, an exoskeleton for finger on wearer's hand and fingers, and a parallel link mechanism for wrist activities between the controller and the exoskeleton.

A. Index finger compliance

Compliance of human index fingertip is measured and the experimental setups are shown in Fig.3. The index finger pushes down a 6-axis force sensor with a certain force, and then the force sensor is pulled by a servo in right direction. The displacement and a reaction force in horizontal direction from the finger are measured. The displacement is finishing within 60[msec], while human finger' reaction time is about 100[msec]. Figure 4 shows the compliance variations of a human index finger in three cases when a grasping force is 2[N], 4[N], and 8[N]. A compliance of human finger varies according to grasping force. The compliance in orthogonal direction to grasping force decreases while grasping force increases. This compliance variation contributes grasping stability and dexterous manipulation. For example, the grasping stability is guaranteed by decreasing the compliance for heavyweight object or by increasing the compliance for an ambiguously-shaped object. Besides, dexterity of human hand has close relationship with compliance variation of the finger.

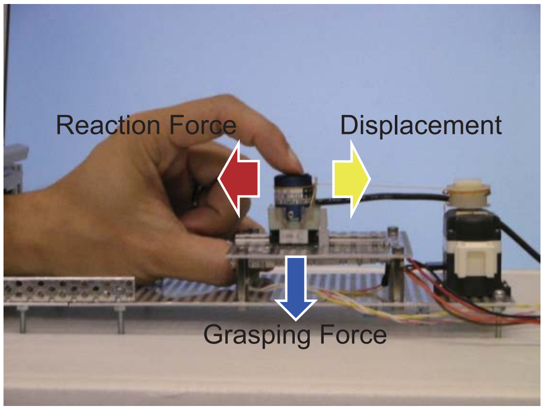

Fig. 3. Experimental setup for variable compliance measurement of index fingertip: a force sensor with six degrees of freedom in mounted on a linear slider. Human index finger pushes down the force sensor, simulating pinching. A reaction force is measured when a force sensor is rapidly pulled to the right by DC motor while an index finger is pushing down the sensor with 2, 4, and 8[N]

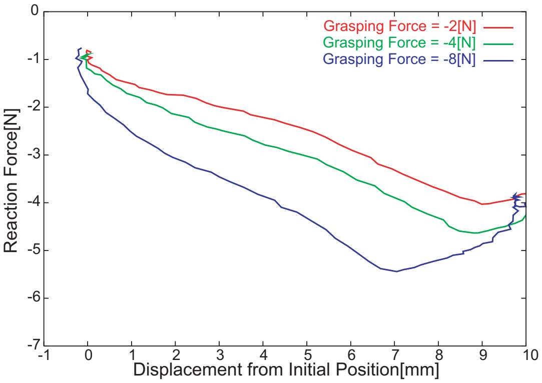

Fig. 4. Human index fingertip compliance in orthogonal direction to a grasping force: The compliance decreases while grasping force increases.

B. Drive mechanism for finger joint

The assistive system should have similar variable compliance to the human finger when the system shares some rates of grasping force with human finger. Because the total grasping system that is composed of human finger and the assistive system should realizes the same property of compliance variation as the human finger itself.

We therefore propose poly-articular tendon drive mechanism to simulate compliance variation of a human finger with simple mechanism. Three tendons shown in Fig. 5 are used and they are pulled by three DC motors independently. Two rings for tendon running are attached on the zero-th link and the first link. The zero-th link is corresponding to a palm. The first tendon "L_1" is connected with the first link through the ring on the zero-th link to rotate the first joint "MP". The second tendon "L_2" is connected with the second link through the ring on zero-th link. It works to rotate the first joint "MP" and second joint "PIP" simultaneously. The third tendon "L_3" is connected with the third link through the ring on the zero-th link and the ring on the first link. It works to rotate three joints of a finger "MP", "PIP" and "DIP" simultaneously. The length of these tendons is adjusted in proportional and derivative control (PD-control) against length error by controlling the corresponding DC motors as if they had elasticity. Figure 8 shows the simulated compliance in orthogonal direction to a grasping force when the grasping force is changed from 2[N] to 8[N]. The stiffness that is inverse value of compliance is changed in proportion to the grasping force, that is similar to human finger. See [6] for further information.

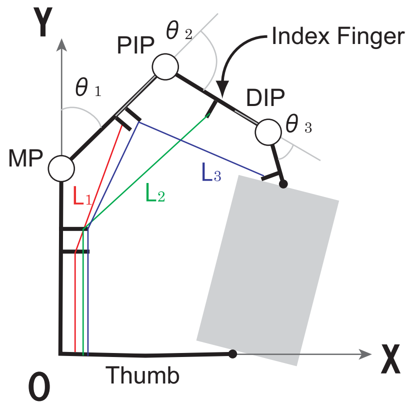

Fig. 5. Tendon-driven mechanism for index finger

An 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 another poly-articular tendon drive mechanism with three DC motors. These six DC motors are mounted on wearer's backhand (Fig. 6), separating into two drive parts: three motors for an index finger and three motors for the three coupled fingers. They are connected by a universal joint that allows fingers to adduct and abduct and allows a palm to deform for finger opposition (Fig. 7).

A thumb is also assisted by exoskeleton with two motors. While CMC joint of human thumb mainly has two degrees of freedom, CMC joint of the exoskeleton is constrained into one DOF by one link and human CMC joint. The one DOF: the opposition of thumb is actuated by a DC motor through another link. IP joint and MP joint of thumb are actuated by another actuator through bi-articular tendon. The thumb exoskeleton has less variable compliance and it works as a rigid finger while grasping, while it synchronizes human thumb motion without force sensor when a power augmentation is not necessary.

C. Drive mechanism for wrist joint

A five-parallel-link mechanism is used to support six wrist joint motions in three degrees of freedom: flexor, extensor, pronator, suprinator, ulnar deviation, and radial deviation.

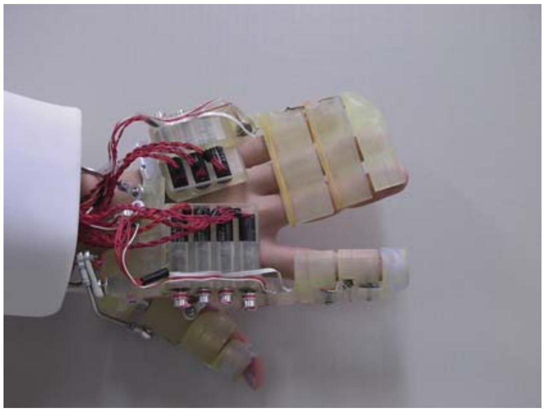

Fig. 6. Adduction and abduction: Index finger drive part and three finger drive part are connected by a universal joint that allows adduction and abduction between an index finger and the three coupled fingers.

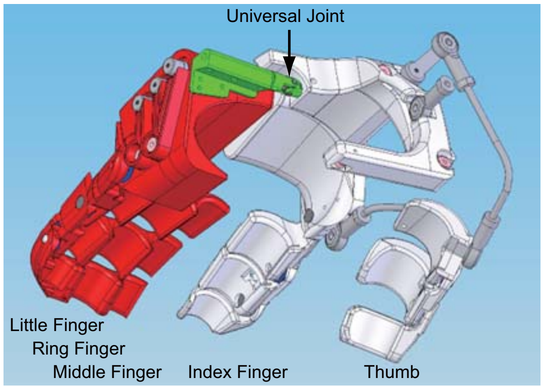

Fig. 7. Opposition: Palm is deformed according to finger motion. The universal joint also allows opposition of a thumb and a little finger as well as adduction/abduction of the three fingers.

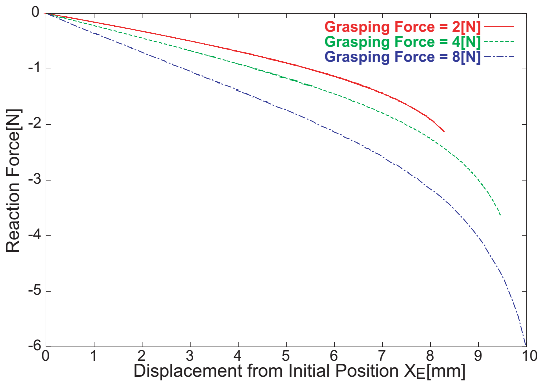

Fig. 8. Index fingertip compliance of the exoskeleton in orthogonal direction to a grasping force

Only five links shown in Fig.9 are enough to assist them because a joint center is fixed by the human wrist joint. The links that connect a finger part with a forearm shell are actuated by three DC motors through reduction gears. The forearm shell that contains controller, motor driver and communication instruments is attached on human forearm. The flexor and extensor “(a)” in Fig. 9 are achieved by rotating the two motors (I) and (II) in the same direction each other. The pronator and suprinator “(b)” are achieved by rotating them in the opposite direction each other. The ulnar deviation and radial deviation “(c)” are principally controlled by the link(III).

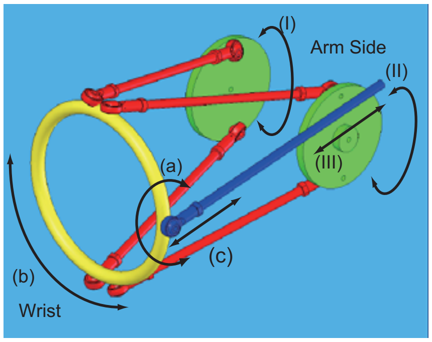

Fig. 9. 5-parallel link for wrist power assist

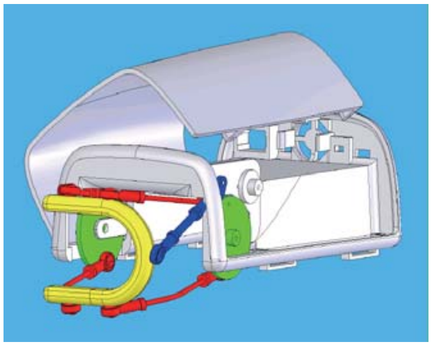

Fig. 10. Parallel link installed in whole system

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 joint. Our developed active electrode shown in Fig. 11 is attached along the corresponding muscles through two Ag/AgCl gel sheets. The active electrode includes an impedance transfer for artifact reduction, amplifier (×10000) and a cut-off filter (100Hz).

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. Precise position and force control of a fingertip becomes important when pinching a small object and the hand support exoskeleton should not disturb the finger motion in this situation. On the contrary, grasping force support of the system becomes necessary when human hand grasps a heavy object with large grasping force. That is it supports grasping force only when force support is necessary for a hard work and it almost vanishes so as not to disturb human hand activity during its precise manipulation.

Fig. 11. Probe for bioelectric potential (built-in instrumentation amplifier)

We therefore propose a bioelectric potential-based switching control that switches two control algorithms for finger part: finger-following control and grasping force control. The grasping force control works only when an integral value of bioelectric potential of lumbricals exceeds a threshold. The integral value of bioelectric potential “IBEP” is calculated by

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

where t is time, T is the 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. 12.

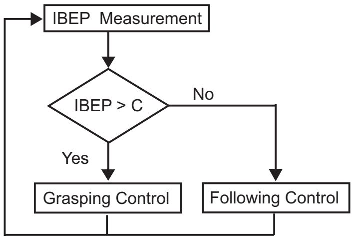

Fig. 12. Bioelectric potential-based switching control

A. Finger-following control

The finger joint of the assistive system is driven by DC motors through wires. The DC motor is not backdrivable due to high reduction gear ratio. Generally a human finger is constrained by the DC motor in this mechanism. However 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 motor.

The control algorithm is as follows; The current finger joint angle θ_i of the assistive system is measured by a potentiometer that is directly installed at each joint. The corresponding wire length L_i to the current joint angle is calculated by using inverse kinematics. Target angle of 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. 13.

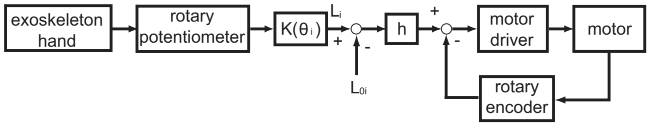

Fig. 13. Block diagram for finger-following control

B. Grasping force control

The grasping force control works only when a bioelectric potential of lumbricals exceeds a threshold. When a bioelectric potential of lumbricals exceeds a threshold, the index finger receives grasping force support from the exoskeleton and the thumb is controlled to keep the joint angles constant.

The direction of grasping force assisted by the exoskeleton is determined according to the relative position with an index fingertip and tip of thumb. The direction becomes from index fingertip to tip of thumb if the index fingertip is further than tip of thumb from a palm as shown in Fig.14. The grasping force direction becomes from index fingertip to a MP of thumb if the index fingertip is nearer than tip of thumb from a palm. 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 lumbricals. Each motor torque required for the desired assistive force is calculated by Jacobian matrix. The block diagram is shown in Fig.15.

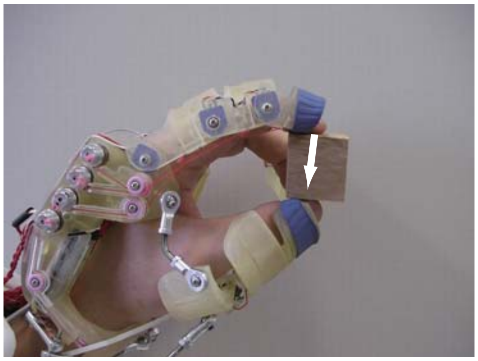

Fig. 14. Grasping force direction during pinching: Arrow means direction of the assistive force(from index fingertip to tip of thumb) when the index fingertip is further than tip of thumb from a palm. The direction becomes from index fingertip to a MP of thumb if the index fingertip is nearer than tip of thumb from a palm.

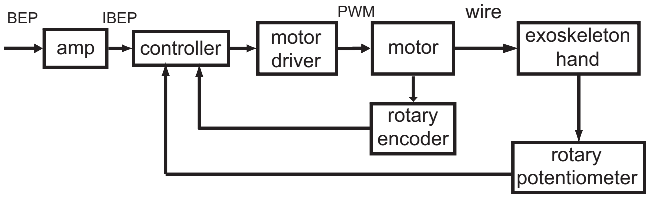

Fig. 15. Block diagram for grasping force control

TABLE I

WORK ANGLE OF THUMB

motion direction	human	human with exoskeleton
opposition	2.5cm - 14.5cm	3cm - 13.5cm
radial abduction	0° - 60°	40°(fixing)
palmar abduction	0° - 90°	40°(fixing)
Flexion (MP)	0° - 60°	0° - 50°
extension (MP)	0° - 10°	0°
Flexion (IP)	0° - 80°	0° - 75°
extension (IP)	0° - 10°	0° - 5°

IV. EXPERIMENTS

A. Bioelectric potential measurement

Flexor carpi radialis contributes flexor and radial deviation, and extensor carpi radialis brevis contributes extensor and radial deviation. Extensor carpi ulnaris contributes extensor and ulnar deviation. The wrist joint posture therefore determines which action each muscle explained above affects.

In this experiment, four active electrodes are attached on representative muscles: lumbricals, flexor carpi radialis, extensor carpi radialis brevis, and extensor carpi ulnaris. A sampling frequency of the bioelectric potential is 1[kHz]. Figure 16 shows the four IBEP when a human hand closes twice and we found that IBEP on channel #1 is active. IBEP on channel #4 becomes active during wrist extension as shown in Fig.17. IBEP on channel #3 becomes active during wrist flexion as shown in Fig.18. IBEP on channel #2 becomes active during wrist ulnar deviation as shown in Fig.19.

B. Following and force control

One additional electrode is mounted on an abductor digiti minimi between MP joint of the little finger and a wrist in order to control grasping force of the index finger and the three coupled fingers independently. Both bioelectric potentials are observed when all fingers grasp an object (Fig. 20), but only corresponding muscle activates when the index finger and the thumb pinch (Fig. 21) or when the little finger and the thumb pinch (Fig. 22).

A wearer confirms that both of the finger-following control and the grasping force control work well and that switching algorithm also work well. He also feels drag from an exoskeleton when he tries to move his finger as fast as possible because rotation speed of DC motor reaches the maximum. The maximum grasping force at fingertip is 5[N]. It is enough to grasp a 500ml pop bottle.

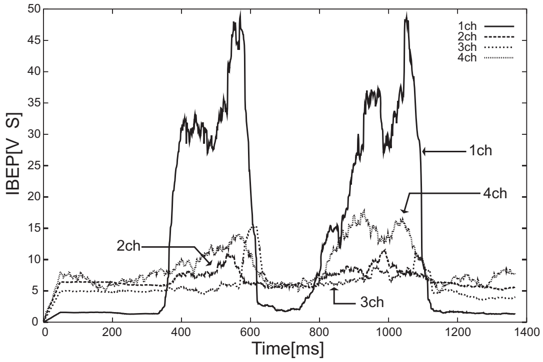

Fig. 16. Integrated bioelectric potential(IBEP) when hand grasps two times: (1ch: lumbricals, 2ch: flexor carpi radialis, 3ch: extensor carpi radialis brevis, 4ch: extensor carpi ulnaris)

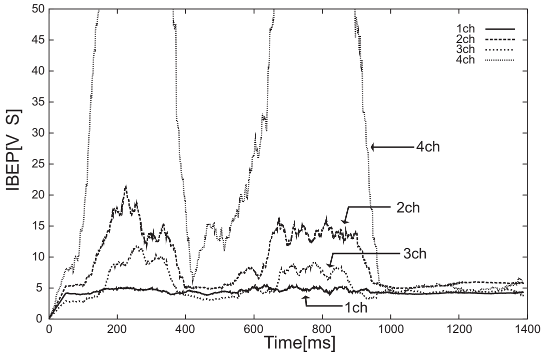

Fig. 17. Integrated bioelectric potential during two wrist extensions

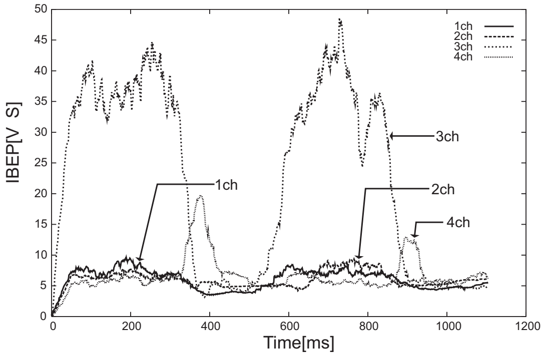

Fig. 18. Integrated bioelectric potential during two wrist flexions

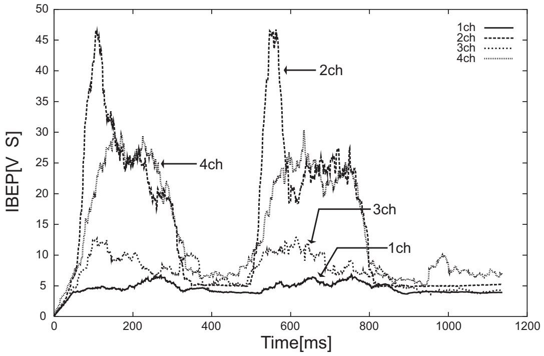

Fig. 19. Integrated bioelectric potential during two wrist ulnar deviations

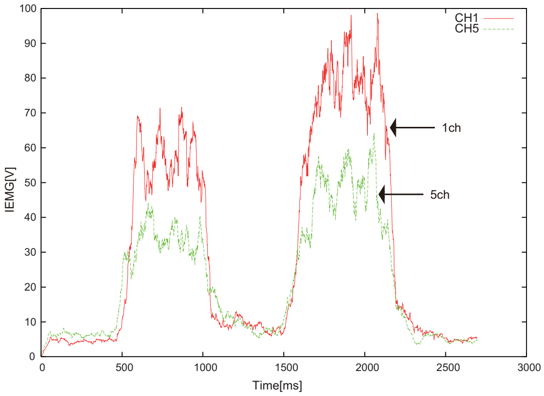

Fig. 20. Integration of bioelectric potential (Whole grasping) Ch 1 is lumbricals between MP joint of an index finger and CMC joint. Ch 5 is an abductor digiti minimi between MP joint of a little finger and a wrist.

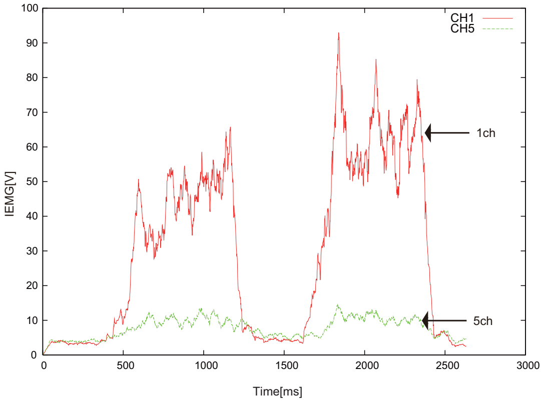

Fig. 21. Integration of bioelectric potential (Pinching with index finger and thumb)

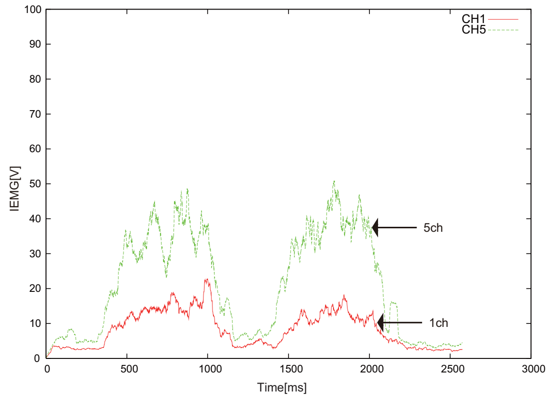

Fig. 22. Integration of bioelectric potential (Pinching with little finger and thumb)

C. *Force control for wrist joint motion*

Four motions of a wrist joint: flexor, extensor, ulnar deviation, and radial deviation are supported by the DC motors through the parallel links and a support torque is based on the IBEP of the corresponding muscle. IBEP of pronator, and suprinator are not measured by our system. This is one of future works. Work angles of each motion are listed on TableII. Those are smaller than operating angles of human wrist.

TABLE II

WORK ANGLES OF WRIST JOINT OF HUMAN AND HAND ASSISTIVE SYSTEM

	Extensor	Flexor	Suprinator	Pronator	Ulnar deviation
Support system	20°	30°	20°	20°	30°
Human wrist	70°	90°	90°	90°	55°

V. CONCLUSIONS

This paper introduced the five-fingered exoskeleton assistive hand that supports human hand and wrist activities. Our proposed poly-articular tendon drive mechanism realizes a mechanical compliance of a human finger so that the total system including a human hand could keep grasping stability. This paper also proposes the new mechanism and the control algorithm so that the system motions could synchronize wearer's hand activities without any force sensor. The poly-articular tendon-driven mechanism and the dual sensing system and the bioelectric potential-based switching control enable wearer's fingers to move freely when they do not contact with any environments. A wearer's fingers receive power support from the system only when a wearer needs a larger grasping force so that the total system could keep dexterity of human hand. Through experiments it was confirmed that a wearer receives power support from the system during grasping and wrist activities.

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