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Evaluation of fingertip force accuracy in different support conditions of exoskeleton

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Abstract— **This paper investigates force accuracy of a human finger in three types of support conditions of an exoskeleton. The exoskeleton augments pinching force of a wearer's index finger in proportion to it based on surface electromyography. Three supporting manners of the pinching force are evaluated by switching a fingertip part of the exoskeleton. One is that the assistive force is applied to the wearer's finger so that the force could be sensible by the wearer. Another case is that the assistive force is directly delivered to a grasping object without a wearer's fingertip. The other is that a part of the force directly affects the object and the rest affects the wearer's finger. Through pilot experiments, transitions of the accuracy through training in these cases are compared each other.**

I. Introduction

Aging population (65 years old or older) is more than 20 percent of whole population in Japan today. This aging society arises from low birthrate rate and long life. In such a situation, elderly people are required to keep working due to serious shortage of labor population. Not only younger person but also healthy elder person has to support social activities. For example, a healthy elder person is requested to physically supports transfer of elderly people from a bed to a wheelchair in domestic site as well as care home. Such a task is heavy for healthy young people and much harder for elder person. Some devices that unweight the care receiver would be helpful in this situation. Some wearable-type support systems are developed to augment caregiver's force for transfer assistance of elder people and physically challenged person in daily activities [1], [2].

A wearable robot which enhances power of human hand is developed. The robot wearing on a human arm can exert quit large grasping force and manipulating force [3]. However wearer's skin does not make a contact with a grasped object directly. Therefore, it is difficult to utilize sensitivity and pliancy of a human hand. The device might be a construction machine in next generation rather than human care machine. The assistive device that works for human care needs flexibilities to hold various shapes like clothes or extremity as well as high precisions of supporting force for safe and comfortable care. There are a few assistive devices to physically support activities of a human arm for daily life and rehabilitation after stroke, using pneumatic rubber artificial muscles[4], [5], and [6]. However all of them do not use voluntary control based on sensory feedback from a hand.

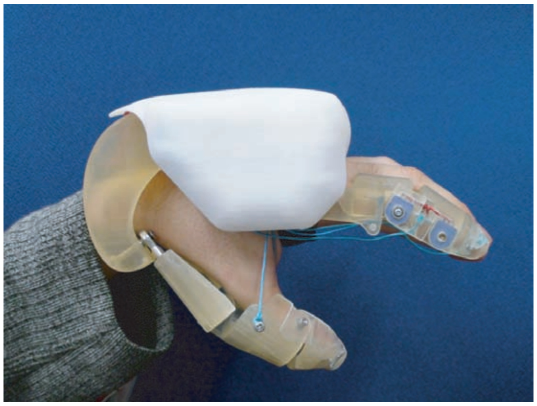

Fig. 1. Wearable hand support system used for force accuracy evaluation

A forearm support system[7] are developed to support activities of a forearm. The system does not cover palm side of a hand with an exoskeleton. Therefore the palm and fingers make a contact with an environment such as a grasping object so that a wearer could control his hand and arm based on his sensory feedback. A tendon-drive mechanism and bioelectric-based switching enables the exoskeleton not to disturb wearer's motion when physical support is not necessary. Each joint of the exoskeleton becomes a almost free joint without any viscous resistance. As a result, skillfulness of a wearer's hand and arm is not lost.

In addition to the sensory feedback and no viscosity, force control is also important items for safe and comfortable support because the device might hurt human body when excessive force is applied to a care receiver. There are a lot of studies on force accuracy of a human hand. For examples, a paper[8] reported the effect of an age factor and a training factor on the modulation of forces produced by the digits with young and older adults. In this study, subjects (young and elder adults) are instructed to track a sine wave force target displayed in a monitor as accurately as possible. Another study[9] reported the relation between force variability and inter-digit individuation in the visual feedback and no visual feedback conditions with young, elderly, and Parkinson's disease participants. Force fluctuations during precision grip are investigated when they try to trace a target force trajectory, looking monitor all the while or partially. However, there are few studies which argue force accuracy in precision grip when an assistive system supports

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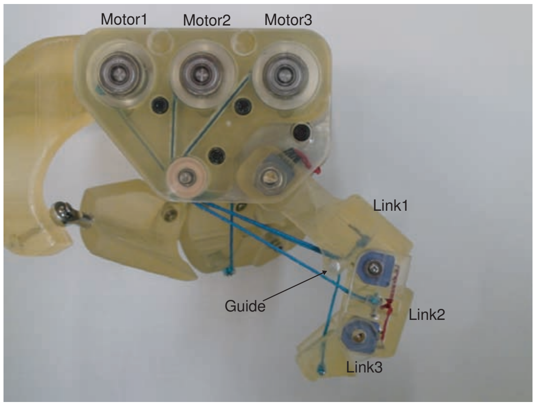

Fig. 2. Sideview of wearable hand support system

TABLE I
SYSTEM SPECIFICATIONS

Motor	Output power	23.2[Watt]
	Nominal voltage	24[Volt]
	Stall torque	139[mNm]
	No-load speed	6,400[rpm]
Gear	Reduction ratio	66:1
	Efficiency	70[%]
Pulley	Radius	9[mm]
Wire	Withstand load	1,200[N]
Grasping force	Between index finger and thumb	480[N]
Weight	Battery exluded	1,215[g]

the force.

This paper therefore investigates the force accuracy of precision grip when human index finger is supported by an exoskeleton. At first, we developed the exoskeleton that exerts the grip force with the maximum force of humans or more. The accuracy of precision grip is measured in three types of support conditions of an exoskeleton. Three supporting manners of the pinching force are evaluated by switching a fingertip part of the exoskeleton. The relationship between fingertip force accuracy and exoskeleton figures are presented in this paper.

II. EXOSKELETON ASSISTIVE SYSTEM

An exoskeleton assistive system is develop to measure the accuracy of fingertip force when a human is supported by the system. In this section, configurations of the assistive system which enhances grasping force (Fig.1) is explained. This system has an exoskeleton for an index finger and a thumb for augmentation and has an active electrode for measurement of a bioelectric potential for estimating a magnitude of an index finger force.

A. Index finger exoskeleton

The larger force an assistive device exerts, the higher pressures an assisted finger receives. Therefore, an assistive system should avoid excessive force on the digits. Thus, the design for the exoskeleton of the support device we developed transmits only a part of assistive force not to press wearer's finger with large force. The index finger exoskeleton covers the upper side (back side of the hand) of the index finger. Both a pad of the index finger and the index finger exoskeleton touches grasping object together. In this way, part of assistive force which is generated by the assistive system is transmitted to the object directly and the rest is delivered through the human finger. The index finger exoskeleton is driven by three motors located on back of a human hand. Besides, the force that comes from these motors transmits via wires. The rotative forces of each motor is delivered to each links (link 1, link 2 and link 3 shown in Fig. 2). The wire connected to the link 3 is connected through a wire guide attached on the link 1. The motor mounting enables to reduce the size of finger exoskeleton as compared with an exoskeleton driven by motors directly. The specifications of drive components are listed on Table I. There are thin type potentiometers at each joint (MP, PIP and DIP joints) in the index finger exoskeleton. These potentiometers measure the angle of each joint to control a length of the wires in a following mode of the switching control.

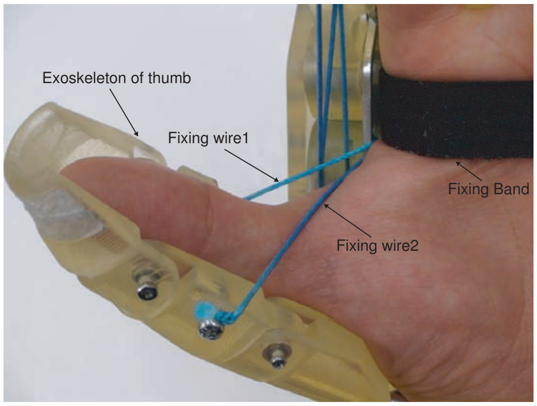

Fig. 3. Two wires to fix thumb at pinching posture

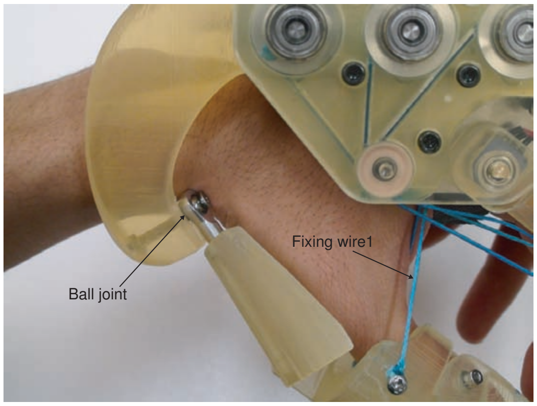

Fig. 4. Ball joint at base of thumb

TABLE II

RANGE OF THUMB'S MOVEMENTS

	Human range	Range with exoskeleton
radial abduction	0° - 60°	60°
palmar abduction	0° - 90°	30°- 45°
CMC joint flexion	-10° - 60°	0°- 60°
IP joint flexion	-10° - 80°	20° - 80°
opposition	0 - 145mm	28 - 145mm

TABLE III

RANGE OF WRIST'S MOVEMENTS

	Human range	Range with exoskeleton
palmar flexion	0° - 90°	0° - 90°
dorsal flexion	0° - 70°	0° - 65°
radial deviation	0° - 25°	0° - 25°
ulnar deviation	0° - 55°	0° - 55°

B. Thumb exoskeleton

The exoskeleton for a thumb covers the upper side of the thumb, similar to the exoskeleton for an index finger. In the same way, both the thumb of a wearer and the thumb part of the exoskeleton touches the target object. Furthermore, only a part of reaction force from a target is transmitted to the human finger, that is, the exoskeleton for a thumb bears the rest of reaction force to realize safety grasping support. The exoskeleton for the thumb is not driven by any actuators. However, it limits extension of CMC joint and IP joint of the thumb at a precision grip posture when grasping an object. Two wires shown in Fig. 3 are used to limit the posture. The thumb is free to move in the rest of direction such as flexion of two joints, adduction and opposition. The joint of the thumb exoskeleton is connected with a base using a ball joint that corresponds to CMC joint of human hand as shown in Fig.4). The ball joint which is located along the rotational axis of CMC joint allows the thumb opponent motion. Table II shows the ranges of thumb's movements. The range of opposition is described as a distance between the thumb fingertip and the MP joint of a little finger. Table III shows the ranges of wrist's movements. Limitation of dorsal flexion of wrist's motion is arisen because the motors located on the back of the hand touch a wearer's forearm.

C. Active electrode for bioelectric potential

A bioelectric potential is measured by surface electrodes for grasping force estimation. Our developed active electrode that includes an impedance transfer for artifact reduction, amplifier (×5000 - 20000), and a band-pass filter is attached along the corresponding muscles via two Ag/AgCl gel sheets. The dimensions of the active electrode is 25 [mm] long, 34 [mm] wide, and 8.5 [mm] high and its weight is 6 [g]. The active electrode is shown in Fig. 5.

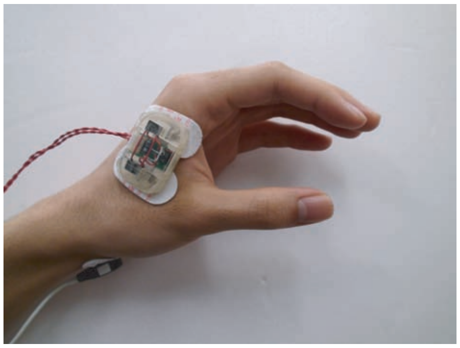

Fig. 5. Active electrode for measurement of bioelectric potential (attached to first dorsal interosseous muscle)

III. BIOELECTRIC POTENTIAL-BASED SWITCHING CONTROL

A human hand has very wide range with regards to finger position and grasping force. Precise position and force control of a fingertip is important when pinching a small and light object. Besides, the exoskeleton should not disturb the finger motion in this situation. On the contrary, it generates large grasping force when a human hand grasps a heavy object for lifting. The exoskeleton should assist the grasping force at this moment. That is the exoskeleton should support grasping force only during its hard works and it should disappear so as not to disturb human hand activities during its precise and dexterous manipulation. We therefore propose a bioelectric potential-based switching control that switches two control algorithms: grasping force control and finger-following control. The grasping force control works only when an integral value of bioelectric potential of first dorsal interosseous muscle exceeds a threshold. The integral value of bioelectric potential V_{IBEP} is calculated by

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

where t is time, T is the accumulation period and $V_{bep}(i)$ is the electric potential measured at time i. The finger-following control is functioning when the grasping force control is not activated.

A. Grasping force control

In the grasping force control mode, the system exerts an assistive force to augment wearer's pinching force. The magnitude of the assistive force is determined by

$$f_{assisst} = \frac{V_{IBEP} - V_{offset}}{V_{IBEP_{max}} - V_{offset}} f_{max}, \tag{2}$$

where f_{max} is the maximum assistive force, $V_{IBEP_{max}}$ is the integral value of bioelectric potential measured at first dorsal interosseous muscle when a subject exerts voluntary maximal force, V_{IBEP} is the integral value of bioelectric potential when the subject works with the system and V_{offset} is a threshold which switches two control algorithms. The assist control mode starts only when V_{IBEP} exceeds V_{offset}.

The direction of grasping force assisted by the exoskeleton is determined according to the relative position with an index fingertip and tip of thumb. Three motors pull three wires individually to generate assistive grasping force of which direction is from an index fingertip to tip of a thumb.

Each motor torque required for the desired assistive force is calculated by Jacobian matrix.

B. Finger-following control

Generally a human motion is constrained by a driving DC motor with a high reduction gear ratio because the motor does not have enough back–drivability due to large friction of the reduction gear. A wire-driven mechanism is therefore used to drive a joint of an exoskeleton, because an exoskeleton can flex and extend freely if a 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 length of the wire.

In the following control mode, the system adjusts the length of wires not to disturb finger motion. To maintain wires relaxed slightly, the assistive system calculates ideal angle of each motor by using the following equations.

$$P_i = h \cdot (L_i - L_{0i}), \tag{3}$$

where L_i is an ideal length of each wire, L_{0i} is a length of initial state (an index finger is fully extended) and h is a constant coefficient which is determined by diameter of a motor pulley and reduction ratio of the motor. L_i determined by the angle of each joint (MP, PIP and DIP) measured by potentiometers correspond to each joint. The voltage applied to motors are calculated by

$$\tau_i = r \cdot (P_i - P_{0i}), \tag{4}$$

where P_{0i} is current value of the rotary encoder and r is a gain to run a proportional control. This mode starts when V_{IBEP} is less than V_{offset}.

IV. EXPERIMENT FOR MEASURING FINGERTIP FORCE ACCURACY

A. Contact conditions of human finger, exoskeleton, and grasping object

We evaluate the accuracy of precision grip force in three types of exoskeletons. Each exoskeleton has different contact condition with a target object. One is that the resultant force is sensible by a wearer as shown in Fig.6. This exoskeleton A does not touch a pinched object. Only human fingers contact the object, that is, whole assistive force generated by the wearable system reaches the target through a subject's finger. Another is that whole assistive force is directly delivered to the grasping object without through fingertip as shown in Fig. 7. This exoskeleton B surrounds a human fingertip, that is, only exoskeleton receives reaction force from an object. In other words, a wearer cannot feel the assistive force. The other is that some force components directly affects the target object and then the rest of the force affects the finger as shown in Fig. 8. Using exoskeleton C, both human finger and the exoskeleton touch an object. As a result, part of force which is generated by assistive system is transmitted to the object directly and the rest is delivered via a human finger.

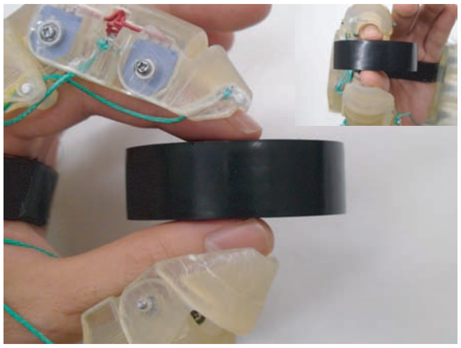

Fig. 6. Exoskeleton A (Only fingers contact an object)

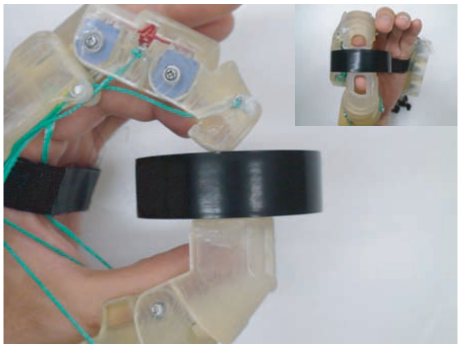

Fig. 7. Exoskeleton B (Only exoskeleton contacts an object)

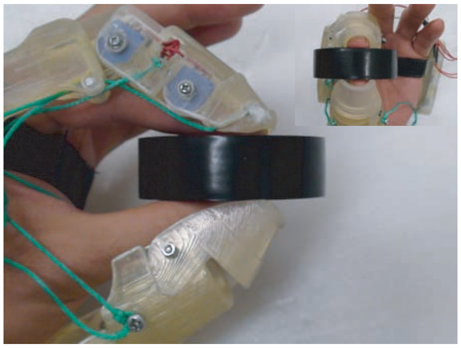

Fig. 8. Exoskeleton C (Fingers and exoskeleton contact an object)

B. Experimental procedure

The maximal griping force f_{max} of each subject [10] is obtained by averaging griping forces that are measured three times. A bioelectric potential of first dorsal interosseous muscle is simultaneously measured. The mean value of these bioelectric potential is $V_{IBEP_{max}}$ in eq.(2). A reference force of resultant force of the human and the assistive system is a half of wearer's maximal pinching force. In other words, the subject exerts the quarter of voluntary maximal force in all cases because the magnitude of an assistive force is the same as subject's force. At the beginning of the experiment, the reference force is informed to a subject verbally. The

Fig. 9. Foot switch

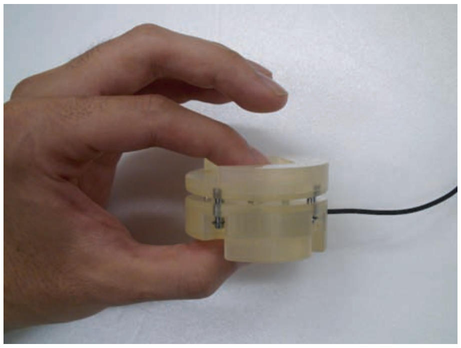

Fig. 10. Measurement device containing a load cell

subject pinches the measurement device to correspond to the reference force given. Furthermore, he steps a foot switch shown in Fig. 9 at the moment that he speculates the total force of human and the assist system correspond to the reference. When the foot switch is turned on, a magnitude of the resultant force measured is recorded. At the same time, a performance of matching force is displayed on a monitor. The performance of matching is calculated by,

$$P_n = \frac{f_n}{f_r} \times 100, \tag{5}$$

where f_n is generated force after n times learning and f_r is a reference pinching force. After stepping a foot switch, a subject stops applying pinching force. Then the subject estimates true value of reference force based on the performance shown in a monitor. After that, the subject pinches a measurement device to match the reference force again. Similarly he steps foot switch to check a performance. Then the performance calculated by the equation (5) is labeled P_1. The subject duplicates these procedure 20 times. We use a measurement device containing a load cell shown in Figure 10 to record a pinching force. Subject uses only his left index finger and thumb to pinch an object without flexing the other fingers. There are three subjects who are male right-handed of twenties.

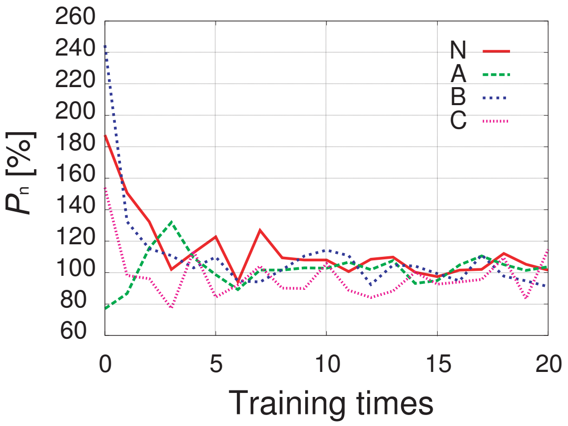

Fig. 11. Performance(Subject1)

TABLE IV
MAXIMUM PINCHING FORCE OF EACH SUBJECT

Subject	1	2	3
Maximum pinching force	42.6[N]	40.8[N]	33.3[N]

C. Experimental results

The maximum pinching force of each subject 1, 2 and 3 without a power assist is listed in Table IV. Subject 1 has already used assistive system in other experiment. Subject 2 and 3 have no experience to wear it on, that is, they are not habituated to it. The graph shown in Fig. 11 is an example of performance transition P_n, which is conducted by Subject 1. The figure shows that force accuracy decreases in the initial state and that it becomes steady state within the fifth training iteration. A normalized mean value of errors in 6-20 times is therefore calculated by

$$E_{6-20} = \frac{\frac{1}{15}\sum_{n=6}^{20} |f_n - f_r|}{f_r} \times 100, \tag{6}$$

where f_n is a generated force after n-th training and f_r is a reference of a pinching force. Figures 12, 13 and 14 are E_{6-20} of Subject 1, 2 and 3, respectively. In these graphs, A, B and C are corresponds to the case supported by the exoskeleton type A, B and C, respectively. On the contrary, N is the case that subjects put off the assistive system and then receive no assistive force. According to these graphs, E_{6-20} is comparatively small in subject 1. The hand and finger postures at the precise griping is constant through the experiment because the subject has enough experience to use the system in advance. On the other hand, E_{6-20} of subject 3 is comparatively large. That is reason why the assistive system forces the hand and finger postures of subject 3 unusual in the experiment. The subject has to take different postures from ones that he is used to be. As to types of the exoskeleton, the exoskeleton A has the smallest error and the exoskeleton C has the largest error except for subject 3. In the case of the exoskeleton A, the subjects feel the

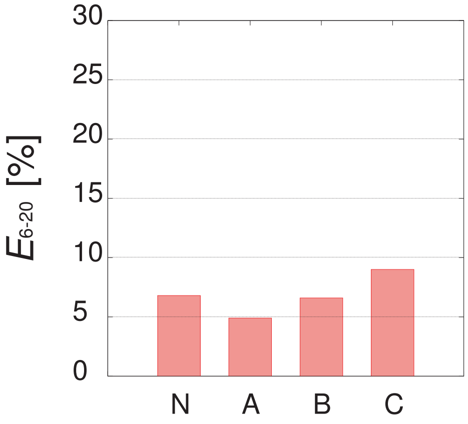

Fig. 12. Error ratio(Subject1)

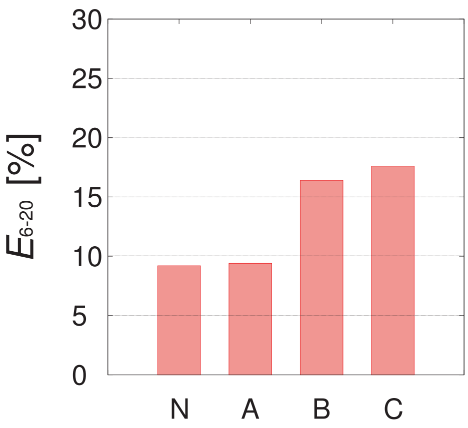

Fig. 13. Error ratio(Subject2)

resultant force of his griping force and system's assistant force, because the exoskeleton A do not touch the target object. In the case of the exoskeleton B, E_{6-20} is larger than those in the case A, because a wearer has to estimate the resultant force based on his griping force. In the case of the exoskeleton C, the precision of the griping force is the worst in three cases. That is reason why a wearer perception is disturbed by the slight change of a finger alignment. Both the human finger and the exoskeleton touch an object and then a part of the assistive force is transmitted to the target directly and the rest is delivered via human finger. However a force distribution is changed by a slight displacement between the human finger and the exoskeleton. As a result, a wear does not feel a consistent resultant force at his fingertip.

V. CONCLUSIONS

This paper investigated the fingertip force accuracy through training when a subject receives assistive force in three supporting manners of exoskeletons. The exoskeleton that exerts a fingertip force based on sEMG are developed for the experiments. From the investigation, the accuracy of pinching force becomes the highest when a wearer feels the total force of the assistive system and the human by transmitting whole assistive force to a target object through a human finger. In addition, it is found that a wearer adjusts his grasping force based on his sensory feedback in short training, within five iterations.

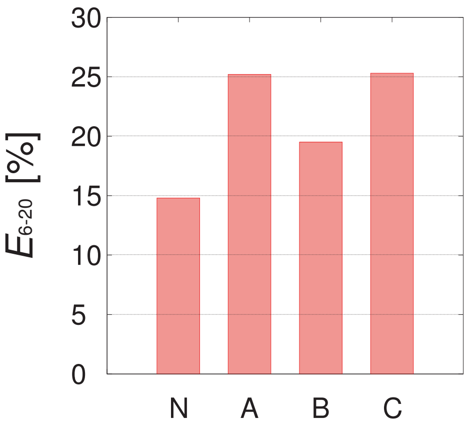

Fig. 14. Error ratio(Subject3)

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