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Superiority of Pinching Force Accuracy Augmented by Exoskeletal Support System

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Abstract— **This paper introduces superiority of pinching force accuracy and band when our developed pinching force support system augments a human's pinching force, allowing direct contact of human fingers and fixing distribution ratio of the supporting force. A user with our exoskeleton support system adjusts his/her pinching force according to a task based on his/her sensory feedback information that is made available by a direct contact with a pinching object. In addition to the direct contact, the exoskeleton pushes a user's finger with a constant rate of supporting force for reduction of the affecting force on the human finger, and then the rest of the supporting force directly acts on the pinching object. In contrast, most of conventional gripping assistive robots interfere with haptic sense of a user finger and with stable and dexterous manipulation based on the tactile sense because they covers a user's fingers with their exoskeleton. Through some experiments, this paper reports that our exoskeleton achieves high precision and wide band of the pinching force, comparing with the human performance and with performance of different structure of the exoskeletons.**

I. INTRODUCTION

Many developed countries are facing on the aged society. As the rate of elderly population increases, demand for care also increases. As a result, many healthy elderly people are engaged in work of care in order to compensate for deficiency of caregivers. The care tasks include physically light-fingered or heavy tasks. For example, a caregiver would help changing clothes or transferring assistances between a bed to a wheelchair or toilet. Some assistive devices are requested by the caregivers since these care tasks are hard work for them. Wearable-type support systems are developed to augment caregiver's force for transferring assistance of elderly people and physically challenged person in daily activities [1], [2].

As for an upper limb support, a wearable robot which is equipped with a human arm such as a powered end effector is developed to exert large gripping and manipulation force [3]. Besides this, the assistive devices using pneumatic rubber artificial muscles are developed to support physical activities of a human arm for daily life and rehabilitation after stroke [4], [5] and [6]. A wearer or a user has to adjust his/her exerting force to achieve flexible motions and tasks, and then these assistive devices have to allow a wearer to adjust the assistive force as requested, by giving him/her enough contact information with an external environment. A direct contact with a grasping object is one of solutions to give a wearer the capability to control his/her force for safe and comfortable support. For example a caregiver holds care-receiver's clothes with fingertips during changing clothes, and holds extremities of a care-receiver or transferring belts with hands during transferring assistance. Sensory feedback and pliancy of a human hand are necessary to make these assistances efficient, comfortable and safe. Kuchenbecker [7] reported that motion control of the finger cannot be controlled precisely when using only visual information, and that the performance improves by using proprioceptive motion feedback in addition to visual information. Jones [8] and Henningsen [9] reported that estimation accuracy of force applied on the surface of a grasping object improves if information on the tactile sense of a fingertip is used for force matching. These papers indicate that sensory feedback including deep sensation is vital factor to improve accuracy of the exerted grasping force. The direct contact of fingertips and a palm with a target object is very important for hand dexterity even if an exoskeleton augments human grasping force.

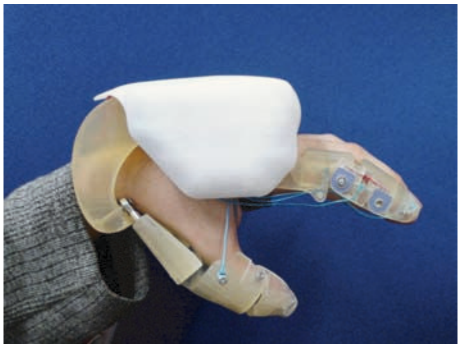

Fig. 1. Wearable hand support system used for force accuracy evaluation

A forearm support system which does not cover palm side of a hand with the exoskeleton has been developed [10]. The palm and fingers make contact with an environment such as a grasping object so that his/her tactile sensory feedback could be used for precise force control for safe, flexible and comfortable support. However, there are few studies that discussed force accuracy of a human hand augmented by a wearable assistive system. Our paper [11] points out pinching force accuracy improves to the certain level through iterative training with three different structures of exoskeletons. The force accuracy transitions of three different supporting manners through learning process are compared in the paper. The next paper [12] introduced a unique structure of a finger

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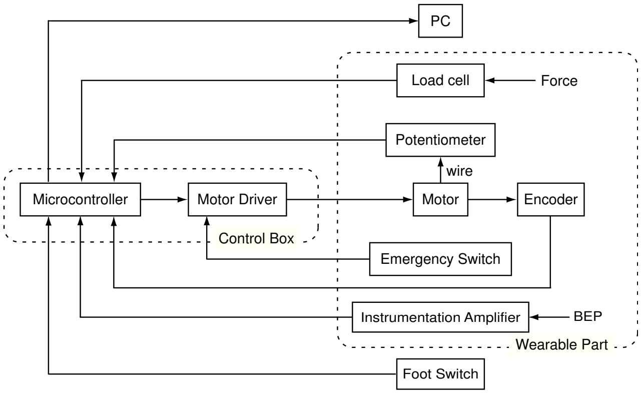

Fig. 2. System architecture of hand support system

exoskeleton that contacts a grasping object and a human finger in order to distribute assistive force to the object directly and to the human finger at constant distribution factor. The structure contributes mitigation of finger skin pressure and improvement of precision of pinching force control. The third paper [13] experimentally showed that thumb sensation contributes improvement of the pinching force accuracy by applying the fixed ratio exoskeleton to the thumb as well as the index finger.

The target pinching force of a wearer was limited to be 25% of MVC (maximum voluntary contraction) in these papers since precisions of human gripping force at various-aged people generally has the best at 22.5% of MVC [14], [15]. Based on these reports, we infer that the best of a gripping force precision could shift to larger grasping force band when a human gripping force is augmented by an assistive device. Because the wearer's exerting force is mitigated by the exoskeleton's augmentation. There is however no argument about influence of pinching force accuracy or importance for sensory feedback at various target forces when the force is augmented. This paper therefore investigates accuracy of the gripping force at various target gripping forces from a band of human's capable gripping force to twice of human's maximal gripping force, that is beyond human capability.

II. EXOSKELETON SUPPORT SYSTEM

A. System configuration of the support system

An exoskeleton support system (Fig. 1) is developed to measure accuracy of fingertip force when a human force is augmented by the system. In this section, configurations of the assistive system which augments grasping force are introduced. Figure 2 shows a system architecture that is divided into a wearable part and a control unit. The control unit is mounted in a separate control box, and is connected to the wearable part by wiring. At the wearable part, the exoskeleton covers the back side of human index finger and thumb and then the exoskeleton of the index finger is actuated by three DC motors through wires as shown in Fig. 3. The torque of each motor is delivered to each link. The wire connected to the link 3 passes through a wire guide attached on the link 1 shown in Fig. 3. A thin type potentiometer (SV01A) is embedded 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. Details of the control algorithm are explained in our previous paper [13].

The exoskeleton for a thumb covers the back side of the thumb in the same way of the index finger. The exoskeleton for the thumb is not driven by any actuators. The thumb, however, generates pinching force since two wires limit extension of CMC and IP joints of the thumb at a precision grip posture as shown in Fig. 4. 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 main exoskeleton using a ball joint that corresponds to CMC joint of the human hand as shown in Fig. 5. The ball joint which is located along the rotational axis of CMC joint allows opponent motion in the thumb.

The system has an active electrode for measurement of a bioelectric potential of first dorsal interosseous muscle for precision gripping force estimation. An assistive force is determined by the human index finger's force. Active electrode specifications are shown in our previous paper [13]. A load cell (LMB-A-100N) is used as the measurement device. It measures from 0 to 10 [kgf] every 5 [gf]. The system specifications are shown in our previous paper [11]. The weight of the wearable part is 1,273 [g].

B. Type of exoskeleton structure for index finger and thumb

A tactile sensory feedback from a hand skin is very important information for us to recognize contact states between a hand and an environment such as a grasping object. The tactile sensory feedback in addition to deep sensation enables us to handle an object with appropriate force safely, carefully and dexterously. A human hand should make direct contact with an environment for the best use of human intelligence. However the direct contact of a human hand with an environment may cause excessive force on the human hand when the exoskeleton thrusts the hand into the environment from back side of the hand with strong force. While the structure that transmits the assistive force to the environment directly ensures safety of a human hand, we do not sense a generating force of the exoskeleton that is very important for the force control. To solve this paradoxical problem, both a pad of the finger and the finger part of the exoskeleton touch the environment. Part of the supporting force generated by the assistive system is transmitted to the environment directly and the rest is delivered to the environment through the human finger. The distribution factor of the two forces should be constant because a wearer has to extrapolate the resultant pinching force including the direct force from the exoskeleton to the environment.

In order to evaluate the accuracy of the fingertip force by satisfying the above requirements to an exoskeleton, three types of fingertip exoskeletons named A, B and E-type are developed. Figure 6 shows the A-type exoskeleton which does not contact with the environment. Whole supporting

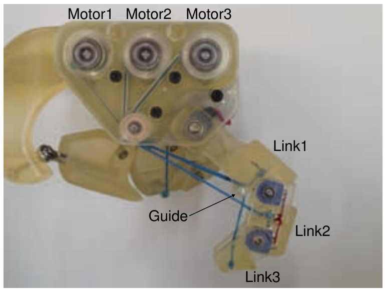

Fig. 3. Side view of hand support system

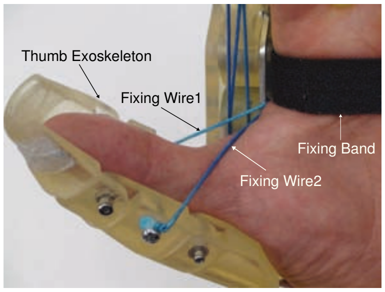

Fig. 4. Two wires to fix thumb at pinching posture

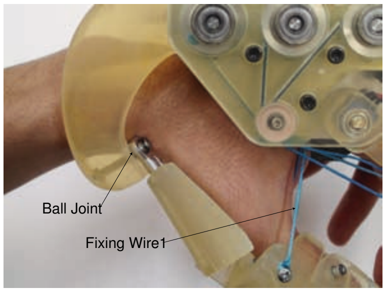

Fig. 5. Ball joint at base of thumb

Fig. 6. Overview of exoskeleton A

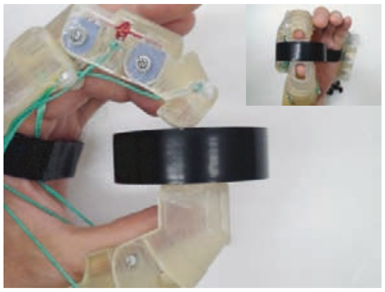

Fig. 7. Overview of exoskeleton B

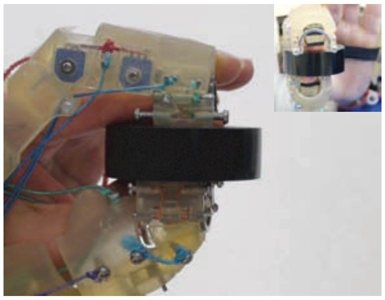

Fig. 8. Overview of exoskeleton E

force acts through a wearer's finger. A human can obtain sensory information from the environment but human fingers are overborne from back side of the hand if the assistive force is large. Figure 7 shows the B-type exoskeleton that surrounds human fingertips. Whole assistive force is directly delivered to the grasping object without through a fingertip and then only the exoskeleton receives reaction force from an environment. As a result, a wearer cannot feel the assistive force. Figure 8 shows the E-type exoskeleton. Both a pad of the index finger and a part of the exoskeleton touch the environment and a fixed portion of supporting force is delivered to the environment through the human finger. The structure of E-type exoskeleton is shown in Fig. 9. The fingertip exoskeleton is composed of three parts: a main exoskeleton, an index finger contact part and an environment contact part. The right and left environment contact parts are fixed each other with a solid link that is a silver-colored arched part. The environment contact part and the finger contact part are connected each other with wires at both right and left sides. The wires do not come off from a shaft of the main exoskeleton since wire guides of the main exoskeleton control the wires position. A nonslip sponge is attached on finger side of the index finger contact part in order to avoid change of the force transmission ratio caused by the slip of a nail of index finger. We adjust the ratio of transmission by changing the thickness of index finger contact part since wearer's finger thickness varies among individuals. An assistive force from the main exoskeleton acts on an intermediate point of the wire. The distribution factor of the supporting force is determined by a horizontal position of the intermediate point. The transmission ratio for an index finger becomes 1.2:1(=$\cos\phi_1$: $\cos\phi_2$) when an inside angle of the exoskeleton, ϕ_1, is 28° and an outside angle, ϕ_2, is 42° in Fig.9. The ratio for a thumb similarly becomes 1.2:1(=$\cos\phi_1$: $\cos\phi_2$) when an inside angle, ϕ_1, is 26° and an outside angle, ϕ_2, is 43°.

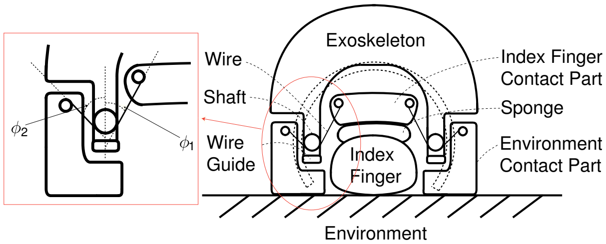

Fig. 9. Structure of E–Type exoskeleton for index finger

C. Sensitivity of transmission ratio to force accuracy

A sensitivity of the distribution factor to the accuracy of gripping force is estimated based on a control model of a human and an assistive system. The block diagram of the control model is shown in Fig. 10. The input signal of this model, $U(s)$, is a target pinching force of the fingertips, and $E(s)$ is the anticipated information of a sensory feedback from the fingertips when a human exerts the target force. The information is generated based on a body schema. The output of the model, $Y(s)$, is an actual gripping force.

In normal condition without any assistance, the anticipated information and the sensory feedback signal are the same each other. The feedback loop therefore works for slight adjustment around the target force. When a human wears the exoskeleton, the total pinching force of a human and the exoskeleton exceeds the target force even if a human exerts the same pinching force as usual, since he/she receives an assistive force from the exoskeleton. The sensory feedback signal, output of G_4, works to decrease the input of the function G_1. Through several training trials, the transfer function G_1 and the anticipated information are updated until the output of the transfer function G_4 becomes zero.

We considered that a steady state of target gripping force after iterative trainings. At the steady state, the output of G_4 becomes 0 and the exerting force of a human and the support system is

$$Y(s) = G_1'(G_2 + G_3)U(s), \tag{1}$$

where G_1' is a updated function of G_1 through learning. The assistive system is designed to exert the same force as a wearer so that a gain of the G_2 and a gain of G_3 are the same each other. The target force, $U(s)$, becomes equal to the total force, $Y(s)$. Therefore $G_1'G_2 = G_1'G_3 = 1/2$. The expectation value $E(s)$ is also updated as follows,

$$E'(s) = G_1'(G_2 r + G_3)G_5 U(s). \tag{2}$$

It is supposed that force transmission ratio r would be changed to αr. The assistive force pushing human finger from back side is $G_1'G_2\alpha r U(s)$. The difference between $E'(s)$ and the sensation of the force to a human finger becomes $G_1'G_2(1-\alpha)rG_5U(s)$. The target force is changed based on this difference. Total error of the assistive force and the human gripping force is therefore $G_1'^2 G_2(G_2 + G_3)G_4G_5(1-\alpha)rU(s)$. This error is simplified into $0.5(1-\alpha)rU(s)$ if a feedback gain, G_4G_5, is equal to 1. The force transmission ratio, r, of the E-type is 0.545. When force transmission ratio changes 20%, the accuracy of grasping force will change about 5.5%.

The E-type exoskeleton distributes the assistive force to the environment and a human finger to avoid excessive force affecting on the human finger. The reduction of the loads to a human finger is

$$R_{reduction} = \frac{1 + ar}{1 + a}, \tag{3}$$

where a is an assistive rate,

$$a = \frac{F_{assist}}{F_{human}}, \tag{4}$$

and r is a force distribution factor.

When the assistive rate, a, is one, a human finger in A-type exoskeleton receives twice of a human exerting force, while a human finger in E-type exoskeleton receive 1.545 times of the human exerting force. The finger's load is reduced by 23%. When the assistive rate becomes four, the finger's load is reduced by 36%.

III. EXPERIMENT FOR FINGERTIP FORCE ACCURACY

A. Experimental environment and conditions

Pinching force accuracy is compared in four conditions. Three types of exoskeletons (A, B, and E) are used for each condition. The other condition is experiment without an assistive system, that is named "case N" as shown in Fig. 11.

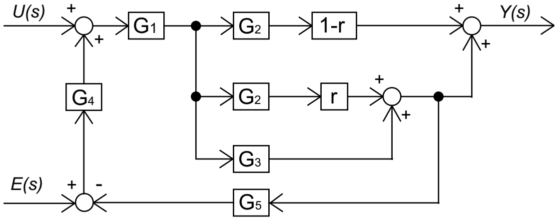

Fig. 10. Block diagram of simplified human's force control with E-type exoskeleton. G_1 is a transfer function which outputs the intensity of muscle activity, receiving a target force that is indicated by a brain as an input signal. G_2 is a transfer function of the exoskeleton to exert the support force based on the intensity of muscle activity. G_3 is a function of a human hand that generates a fingertip force of human based on the intensity of muscle activity from the brain. G_4 is a conversion function to adjust the target force based on discrepancy between an anticipated sensation and sensory feedback information. G_5 is a transfer function from a fingertip pressure to sensory feedback. r is the distribution factor of the assistive force.

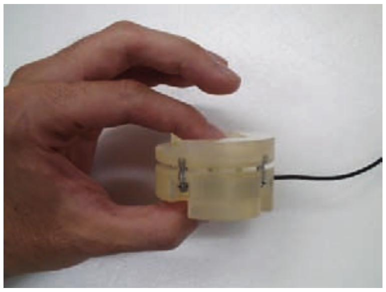

Fig. 11. Measurement device with a load cell

The experiment is conducted with four subjects who are male and right-handed between 20 and 30 years old. The electrodes are attached to the first dorsal interosseous muscle of the left hand as a preparation for the experiment. The maximal gripping force f_{max} (MVC) with each subjects [16] is measured with a load cell between the thumb and the index finger. The MVC is a mean value of maximal gripping forces measured in three trials. The assistive rate is regulated so that the system could exert the same force as a human exerting force.

Firstly, the reference force is informed to a subject verbally. The subject tries to pinch the measurement device with the corresponding to the reference force. The subject steps a foot switch at the moment that he speculates the total force of a human and the assist system correspond to the reference. When the foot switch is turned on, the resultant force is measured and recorded. After stepping a foot switch, the subject stops applying pinching force. When he stops pinching, a performance of matching is displayed on a monitor in front of him. 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. The performance of the first trial becomes P_0. Secondly, the subject estimates true value of reference force based on the performance shown in the monitor. After that, the subject starts pinching a measurement device again to match the reference force. Similarly he

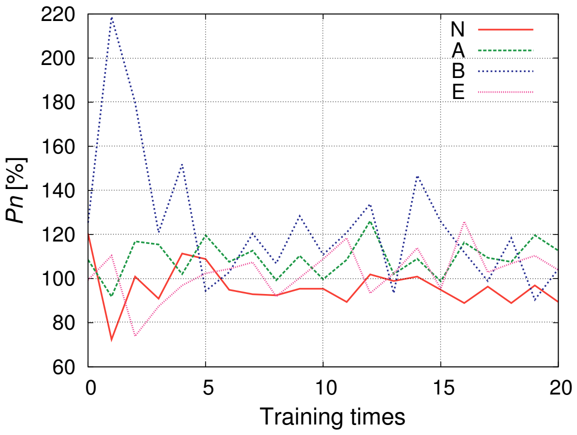

Fig. 12. Learning curve of subject 1

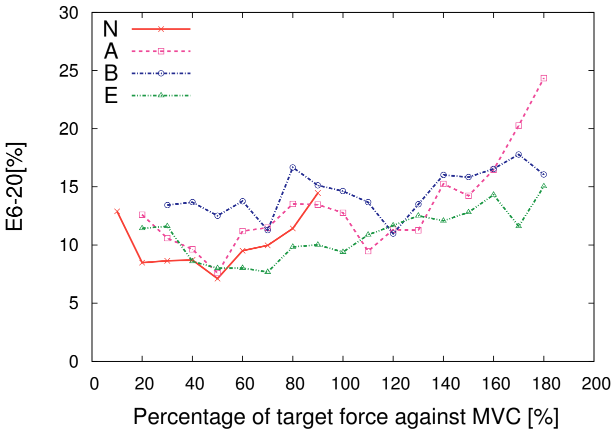

Fig. 13. Result of subject 1. MVC value of subject 1 is 2697[gf].

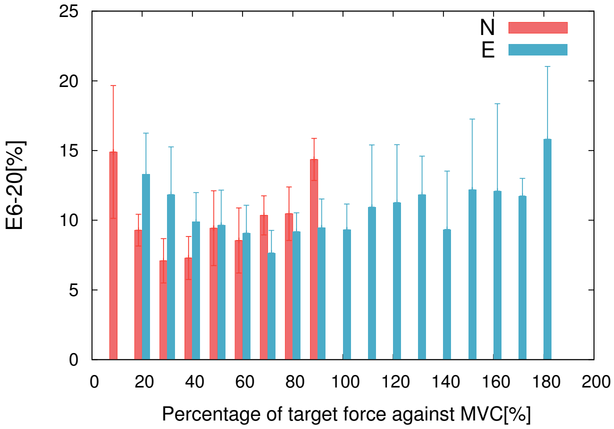

Fig. 14. Mean and standard deviation of all subjects

steps the foot switch to measure the performance. Then the performance calculated by (5) is labeled P_1. The subject duplicates these procedure 20 times. All subjects pinch the measurement device without flexion of the other fingers. As soon as a measurement finishes, a subject will rest about two minutes. Then the next reference force is informed to a subject.

The target gripping force is set at every 10% against maximal gripping force. The force that human cannot exert 20 times is excluded such as 100% of MVC. The order of the experiment conditions is selected in a random and the sequence of A, B and E-type and case N is also at random.

B. Learning curve through trials

Figure 12 shows an example of performance transitions of P_n through the trials, which is conducted by subject 1. The target force is 40% of MVC. The figure shows that force error decreases in a few trials and that it is in a steady state after the sixth trials. A normalized mean value of errors in 6th to 20th trials is therefore calculated for an evaluation by

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

where f_n is the resultant force after n-th trial and f_r is a reference of a pinching force.

C. Experimental results

The MVC values of subject 1, 2, 3 and 4 were 2697, 3120, 2235, and 3358 [gf], respectively. The gripping force accuracies of subject 1 in four conditions are measured for comparison. Figure 13 shows the result of the subject. B-type has higher error rate regardless of the band of target force than other conditions because B-type cannot give the subject sensory information about the supporting force. The error rate of the A-type becomes higher than that of the E-type when the target force is large (especially from 160 to 180% of MVC). The E-type is superior to the A and B-types because it stably maintains the better accuracy at various target force in three cases.

The pinching force accuracies of the other three subjects are measured in two conditions: with the E-type exoskeleton and without the exoskeleton. The means and the standard deviations of the gripping force accuracies of four subjects are shown in Fig. 14. p values of the pared t–test at each target force are as follows: $p = 0.024$ in 70% of the MVC, $p = 0.039$ in 80% of the MVC and $p = 0.002$ in 90% of the MVC. The E-type significantly has lower error than case N among 70, 80 and 90% of the MVC. The accuracy of the E-type at more than 100% of the MVC is maintained at the same level as the case N of the corresponding force. For example, the accuracy of the E-type at 180% is similar to the accuracy of the case N at 90%.

IV. DISCUSSION

The experimental results show that pinching force accuracy of case N became the best at 30–40% of the MVC and that it gradually got worse monotonically as the target force increases. A cause to conduct this result about gripping force accuracy depending on the size of target force is Fechner's law that says the magnitude of a subjective sensation increases proportional to the logarithm of the stimulus intensity. Discrepancy between the target force and actual gripping force in the large target force band is felt smaller than actual one by the human sensory system.

A subject with the assistive system just has to exert a half of the target force in this experiments. The accuracy of the total gripping force is dependent on accuracy of a human's finger force control. The subjects with the E-type could estimate the total gripping force based on their own sensory feedback. Figure 12 shows that subjects could accurately estimate the total force, that is, the fixed distribution factor of the assistive force enables a human to estimate the force. In the small target force band, the error rate of the E-type is however bigger than that of case N. The reason is that the assistive system cannot estimate subjects' pinching force precisely since a bioelectrical signal at less than 20% of MVC becomes small and signal-to-noise ratio is also small. The assistive system therefore did not augment subjects' force exactly. One method to overcome the big error is to reduce the assistive rate of the system in that range because there is no need for a healthy person to support in the range 20–40% of MVC. When the target force is set from 70% to 90%, the accuracy of the E-type is superior to case N, because the target force band is corresponding to the most precise band of human finger. When the target force is more than 100%, the error of E-type is almost same as one of case N at 10% or 90%, while the error of A-type increases drastically because of saturation of the fingertip deformation. The large assistive force of the A-type presses down the fingertip almost completely so that the deformation of the fingertip is nearly saturated. As a result, a user's sensitivity to discriminate change of the force is getting worse in the large target force band.

The 23% load reduction of the E-type enables a human to discriminate precisely even if the target force is 180% because the load of the A-type at 140% corresponds one of the E-type of 180%. The E-type also has the saturation of the deformation around 200% because the saturation of the A-type starts 160%. The saturation can be avoided by changing the distribution factor even if the assistive system exerts larger force by increasing the assistive rate. For example, when the assistive rate is set two, the appropriate distribution factor becomes 1:3.

In the future works, we find appropriate factor of the force distribution according to the assistive rate and the target force from viewpoint of the magnitude of a subjective sensation and saturation of finger deformation.

V. CONCLUSION

This paper focused on accuracy of gripping force control of an index finger and a thumb, and confirmed superiority of force accuracy and the extended band of grasping force when using our developed assistive system.

According to the experimental results of A-type, B-type and case N, it is confirmed that pinching force accuracy was kept at the same as human's accuracy in the ordinary force band if sensory feedback from both fingers are consistent. In the extended force band such as 170% and 180%, the accuracy of the A-type got worse due to excessive force affecting on the fingertips. On the contrary, the E-type which reduces the affecting force on the human finger improved the pinching force accuracy around 170% and achieve the same accuracy of the human around 80%.

Our exoskeleton achieves higher precision and extends range of the human pinching force.

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