Accuracy Improvement of Pinching Force Augmentation by Exoskeleton

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Abstract—This paper proposes a support structure for a wearer to precisely control a pinching force with the support of an exoskeleton, which augments human pinching force based on a surface electromyography. A human hand should make a direct contact with the environment for the best use of human intelligence because a tactile sensory feedback from the hand is very important information for a human to handle it accurately and dexterously. However the direct contact may bring excessive force on the human finger when the exoskeleton thrusts the finger into the environment with strong force. This paper proposes the best support structure, type D, by investigating accuracy of a human pinching force with four different types of exoskeletons. They allow the finger to directly contact the environment but force transfer paths from the exoskeleton to the environment are different in each other. Through pilot experiments, the exoskeleton that supports more precise force control and safer manipulation is proposed.

I. INTRODUCTION

Aging population (65 years old or older) is more than 20 percent of whole population of Japan today. This aging society arises from low birthrate and long life expectancy. In such a situation, elderly people are required to keep working owing to serious shortage of labor population. Not only a young person but also a healthy elder person has to support social activities. For example, a healthy elder person is requested to physically support transfer of others from a bed to a wheelchair in domestic site as well as care home. Such a task is hard work 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 on a human arm can exert quite large grasping and manipulating force [3]. However wearer’s skin does not make a contact with a grasped object directly. It is therefore difficult to utilize sensitivity and pliancy of a human hand. The device might be a next-generation construction machine rather than human care machine. The assistive device that works for human care needs flexibility to hold various shapes like clothes or extremities as well as high precisions of supporting force for safe and comfortable care. In addition, human controls his/her hands intelligently based on the tactile sensory feedbacks from the hands, when the hands make a direct contact with an environment. 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 neither of them uses voluntary control based on sensory feedback from a hand.

A forearm support system[7] is developed to support activities of a forearm. The system does not cover palm side of a hand with the exoskeleton. Therefore the palm and fingers make contact with an environment such as a grasping object so that a wearer could control his/her hand and arm based on his/her tactile 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 an almost free joint without any viscous resistance. As a result, skillfulness of a wearer’s hand and arm is preserved. In addition to the tactile sensory feedback and no viscosity, force control is also important function for safe, flexible 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 example, [8] reported the effect of an age factor and a training factor on the modulation of forces produced by the digits with young and elder adults. In the 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 relationship 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 at a monitor all the time or partially. However, there are few studies which argue force accuracy in precision grip when the force is augmented by an assistive system. Our paper[10] points out importance of force transfer path from an exoskeleton to an environment by investigating force accuracy of precision grip when an index finger is supported by three different types of exoskeletons.

This paper proposes a support structure for a wearer to precisely control his/her pinching force of the precision grip with the support of an exoskeleton. The rest of this paper is organized as follows. In section 2, we introduce configurations of a pinching-force assistive system used for experiments. Section 3 briefly describes a bioelectric potential-based switching control for force augmentation. Finally, we measure the force accuracy of the proposed exoskeleton and then compare the performance of it with performance of the conventional exoskeletons.

II. EXOSKELETON ASSISTIVE SYSTEM

An exoskeleton assistive system is developed to measure the 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 (Fig.1) is introduced.

The exoskeleton covers the upper side (back side of the hand) 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.2. The system has an active electrode for measurement of a bioelectric potential of a muscle for estimating a magnitude of a human index finger’s force. An assistive force is determined by the human index finger’s force. The system specifications are shown in our previous paper[10]. The weight of the system is 1,235 gram.

A. Proposed fingertip exoskeleton of index finger

A tactile sensory feedback from a hand is very important information for us to recognize contact states between a human hand and an environment such as a grasping object. The tactile sensory feedback in addition to somatosensory feedback enables us to handle an object with appropriate force safely and dexterously. A human hand should make a 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. In an opposite manner, we do not sense a generating force of the exoskeleton if the exoskeleton prevents the hand from making the direct contact with the environment.

To solve this paradoxical problem, both a pad of the index finger and the index finger part of the exoskeleton touch the environment. Part of the assistive force generated
The proposed structure of the exoskeleton is shown in Fig.3. The fingertip exoskeleton is composed of three parts: a main exoskeleton, a 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 black-colored arched part in Fig.4. The environment contact part and the finger contact part are connected each other with two wires at both right and left sides. An assistive force from the main exoskeleton acts on an intermediate point of the wire. The distribution factor of the assistive force is determined by a horizontal position of the intermediate point. It becomes 1:1.19 (\(\cos \theta_1 : \cos \theta_2\)) when an angle inside the exoskeleton, \(\theta_1\), is 28° and an angle outside the exoskeleton, \(\theta_2\), is 42° in Fig.5.

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 torque of each motor is delivered to each link (link 1, link 2 and link 3 shown in Fig.2). The wire connected to the link 3 passes through a wire guide attached on the link 1. 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.

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 touch the environment. Furthermore, only a part of reaction force from the environment 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, two wires limit extension of CMC joint and IP joint of the thumb at a precision grip posture at a grasping posture as shown in Fig.6. 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.7. The ball joint which is located along the rotational axis of CMC joint allows the thumb opponent motion.

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.8.
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 the precise and dexterous manipulation. We therefore use 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

\[
f_{assist} = \frac{V_{IBEP} - V_{offset}}{V_{IBEP_{max}} - V_{offset}} f_{max}, \tag{2}
\]

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 using 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 is 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 FINGERTIP FORCE ACCURACY

A. Experimental procedure

We evaluate the accuracy of precision grip force with the proposed exoskeleton by comparing it with three types of exoskeletons. Each exoskeleton has different contact states with an environment.

One is that the resultant force is sensible by a wearer as shown in Fig.10. This exoskeleton type \( A \) does not touch a pinched object. Only human fingers contact the object, that is, whole assistive force generated by the assistive 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.11. This exoskeleton type \( B \) surrounds a human fingertip, that is, only the exoskeleton receives reaction force from an environment. In other words, a wearer cannot feel the assistive force. The other is that some force components directly affects the environment and then the rest of the force affects the finger as shown in Fig.12. Using this exoskeleton type \( C \), both human finger and the exoskeleton make a contact with the environment. As a result, part of force which is generated by the assistive system is transmitted to the environment directly and the rest is delivered via a human finger.

At first, we obtain the maximal gripping force \( f_{max} \) of each subject [11] by averaging griping forces of three trials. A bioelectric potential of first dorsal interosseous muscle is simultaneously measured. The mean value of these bioelectric potential becomes \( V_{IBEP_{max}} \). 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 the voluntary maximal force in all cases because the magnitude of an assistive force is the same as subject’s force. The reference force becomes a quarter of the voluntary maximal force only when the subject pinches an object without any assistance as shown in Fig.9. That is a case \( N \).

Secondly, the reference force is informed to a subject verbally. The subject tries to pinch the measurement device with the corresponding reference force. A load cell is in the measurement device. He steps a foot switch 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, the resultant force is measured and recorded. After
stepping a foot switch, a 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,

\[ P_n = \frac{f_n}{f_r} \times 100, \quad (5) \]

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 \( P_0 \).

Thirdly, 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 steps the foot switch to measure the performance. Then the performance calculated by the equation (5) is labeled \( P_1 \). The subject duplicates these procedure 20 times.

The experiment is conducted with five subjects who are male and right-handed between 20 and 30 years old. All subjects use his left index finger and thumb to pinch the measurement device without flexion of the other fingers.

**B. Learning curve through trials**

The graph shown in Fig.13 is an example of performance shift of \( P_n \), which is conducted by Subject 1. The figure shows that force errors decrease in the initial states and that they are in a steady state before the fifth trial. A normalized mean value of errors in 6-20 times is therefore calculated by

\[ E_{6-20} = \frac{1}{15} \sum_{n=6}^{20} \left| \frac{f_n - f_r}{f_r} \right| \times 100, \quad (6) \]

where \( f_n \) is the resultant force after \( n \)-th trial and \( f_r \) is a reference of a pinching force. Figures IV-B-IV-B are \( E_{6-20} \) of Subject 1-5, respectively. In these graphs, \( A \), \( B \) and \( C \) are corresponds to the case supported by the exoskeleton types \( A \), \( B \) and \( C \), respectively. On the contrary, \( N \) is a normal case that subjects put off the assistive system and then receive no assistive force.

The exoskeleton type \( A \) has the smallest error except for a normal case \( N \) because the subjects control the resultant force, by updating a reference table to represent a relationship between own tactile feel and the resultant force. In the case of the exoskeleton type \( B \), \( E_{6-20} \) is larger than those in the case \( A \), because a wearer has to estimate the assistive force of the exoskeleton without a real feeling. In the case of the exoskeleton type \( C \), the precision of the grasping force is the worst in three cases because wearer’s 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 the human finger. However a force distribution is changed by a slight displacement between the human finger and the exoskeleton. As a result, a wearer does not develop a consistent reference table based on his sensory feedback.

**C. Performance of the proposed exoskeleton**

In the same way as the previous experiments, the proposed structure, type \( D \), is evaluated. The type \( A \) or the case \( N \) has the best performance and the type \( C \) has the worst in the previous experiments. The performance of the type \( D \) is therefore compared with case \( N \) and the type \( C \). The results are shown in Fig.15. All of significant levels among the type \( D \), the case \( N \) and the type \( C \) are less than 0.05 as shown in Fig.16. Our proposed exoskeleton performs better than the previous exoskeleton type \( C \) but the type \( A \) is better than our proposed exoskeleton. Type \( A \) has the best performance on the force accuracy. However an upper limitation of the assistive force of type \( A \) should be reduced by 33 percent, because all assistive force of type \( A \) acts on a human finger while a half of the assistive force of type \( D \) acts on a human finger.

**V. Conclusions**

This paper proposed a support structure for a wearer to precisely and safely control the resultant pinching force. The
proposed structure, type $D$, satisfied the two requirements about the contact condition and the force limitation applied to a human finger. The experiments showed that the proposed exoskeleton has better performance than the previous exoskeleton. However we need some works for the exoskeleton with a human to get the same performance as human own performance from viewpoint of the force accuracy.

REFERENCES