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Paper:

Development of Soft Power-Assist Glove and Control Based on Human Intent

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The purpose of this study is to develop a soft-material power-assist glove for hand grasping in daily life by older or disabled persons. Such a glove must be compact, lightweight, and flexible. The glove we developed consists of rubber and cloth, and is user-friendly. This paper describes the types of rubber muscle and the soft power-assist glove, together with control based on human intent and the effectiveness of our proposal.

Keywords: wearable robot, welfare robot, artificial pneumatic rubber muscle, power-assist wear, hand motion

1. Introduction

Population aging has led to a shortage of caregivers and an excess of daily problems with increasing age such as paralysis due to weakened muscles, cerebral stroke, etc. Finger activity vital to eating, cosmetic activity, etc., is adversely affected by a loss in finger pinching strength decreasing to 50% of peak force at age 50 [1]. Finger flexion and extension must thus be assisted to sustain independent living. Finger assistance should, for example, be flexible, lightweight, and wearable if directly attached to the fingers. Pneumatic actuators are suitable for the above applications because they are lightweight and capable of high force.

Grip-amplified gloves using bi-articular mechanism [2] and power-assisted gloves for supporting grip strength [3] have been developed using linear motion pneumatic actuators. These devices, however, require an exoskeleton to convert linear motion to rotational motion, which increases size and weight. Devices for assisting daily living are thus preferably compact, lightweight, flexible, and without exoskeletons.

The power-assist glove we developed has a curved actuator requiring no exoskeleton for converting linear motion to rotational motion [4]. A sheet-like curved rubber muscle of woven rubber and cloth makes the glove compact, lightweight, and flexible [5].

Devices assisting finger flexion and extension require a wide-ranging flexion angle, so we developed a novel spiral rubber muscle capable of flexion at the thumb base. Devices with rubber muscles enable wearers to grasp objects easily. Among the devices developed to support rehabilitation realizing a wide-ranging finger flexion angle based on the wearer's intent, one supports rehabilitation replicating the finger joint angle acquired by a data glove [6].

Rehabilitation assistance devices may not need to be compact, but those assisting in daily living must be. No study has been made, to our knowledge, for developing a compact device covering a wide finger flexion angle range. We propose finding a target finger flexion angle for the power-assist glove by acquiring information on finger flexion angles using the data glove.

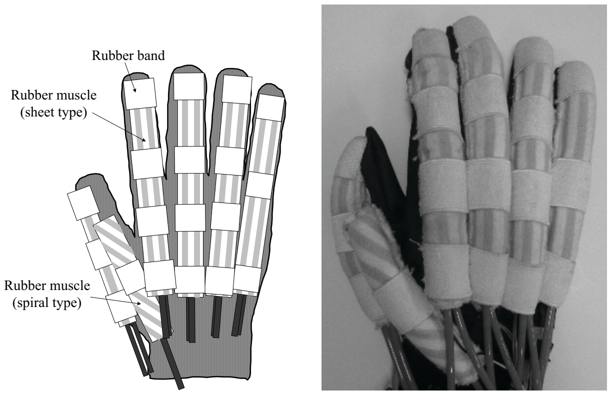
We also propose reflecting wearer intent using electromyography (EMG), because control that the wearer can operate sensuously is required. An approach has been already proposed for assisting grasping by the fingers based on forearm EMG [7]. However, because the forearm includes muscles for wrist activity in addition to the finger activity, the device may mistakenly judge that the finger was moved when, in fact, the wearer moved the wrist. A device can be developed to selectively assist the finger reflecting wearer intent if it can be judged what activity the wearer is undertaking. Our study verifies finger activity and its identification.

We begin with an overview of the power-assist glove, then describe the sheet-like curved and spiral rubber muscles and features of the power-assist glove including these artificial muscles. We also propose control with the data glove and that with EMG based on wearer intent, and verify their effectiveness.

2. Power-Assist Glove

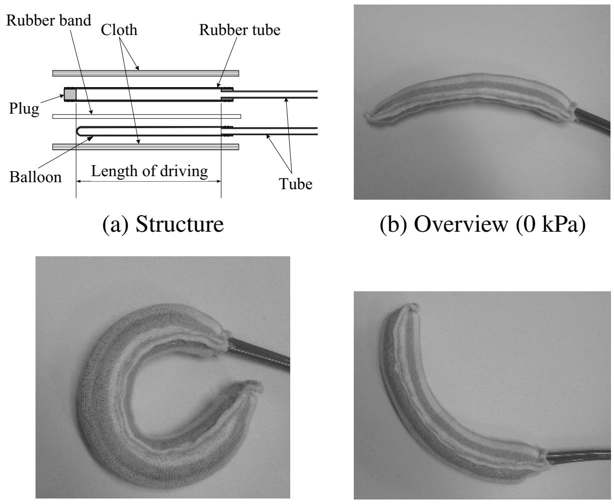
2.1. Structure

Figure 1 shows the power-assist glove we developed, which has sheet-like curved rubber muscles for assisting flexion and extension and the spiral rubber muscle we developed for assisting opponens pollicis motion. The sheet-like curved rubber muscle is fixed on the synthetic leather glove via woven rubber. The spiral rubber muscle is fixed with both ends sewn on the glove. These muscles are on the back of the hand and rarely interfere with grasping. The device weighs just 135 g.



(a) Structure (b) Overview

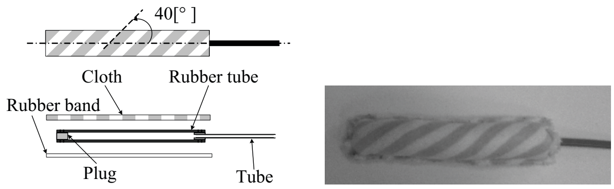
Fig. 1. Power-assist glove.



(a) Structure (b) Overview (0 kPa)

(c) Flexion (250 kPa) (d) Extension (150 kPa)

Fig. 2. Sheet-like curved rubber muscle.



(a) Structure (b) Overview

Fig. 3. Spiral rubber muscle.

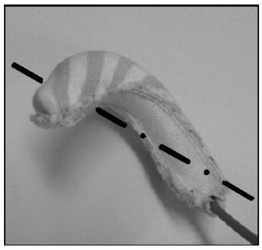
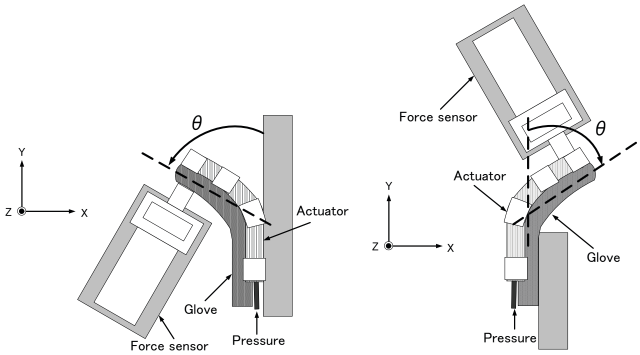


Fig. 4. Spiral rubber muscle movement.



(a) Flexion (b) Extension

Fig. 5. Experimental equipment: top.

2.2. Sheet-Like Curved Rubber Muscle

The double-layer sheet-like curved rubber muscle has a rubber tube and balloon between the woven rubber and cloth as shown in **Fig. 2(a)**. The durable double-layer balloon is flat without pressure applied to contact the back of the wearer's hand. The muscle is covered with woven rubber and cloth selectively extending longitudinally to suppress radial expansion under pressure. The cloth extends beyond the woven rubber and the difference enables the muscle to extend while being flexed. **Fig. 2(c)** shows the muscle flexion in **Fig. 2(a)** when the rubber tube is under a pressure of 250 kPa. **Fig. 2(d)** shows extension when the balloon is under a pressure of 150 kPa.

The sheet-like curved rubber muscle has length of droving of 80 mm (thumb), 140 mm (index finger), 150 mm (middle finger), 130 mm (ring finger), and 110 mm (little finger). Each rubber muscle uses a rubber tube 8.4 mm in outer diameter and 6.0 mm in inner diameter.

2.3. Spiral Rubber Muscle

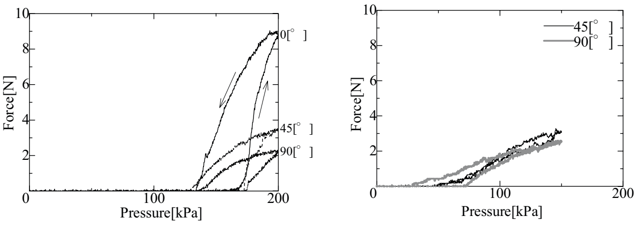
The spiral rubber muscle consists of a rubber tube covered with woven rubber and cloth as shown in **Fig. 3(a)**. The artificial muscle flexes because of the differential expansion coefficient between the woven rubber and cloth. A conventional sheet-like curved rubber muscle flexes with both ends mutually approaching on a plane (**Fig. 2(c)**). The spiral rubber muscle we developed has the end spiral around the dot-dash line (**Fig. 4**) as the hypothetical axis by using the cloth covering the muscle with slanted 40° to the axis.

The spiral rubber muscle has a length of driving of 80 mm, and uses a rubber tube 8.4 mm in outer diameter and 6.0 mm in inner diameter.

3. Basic Glove Characteristics

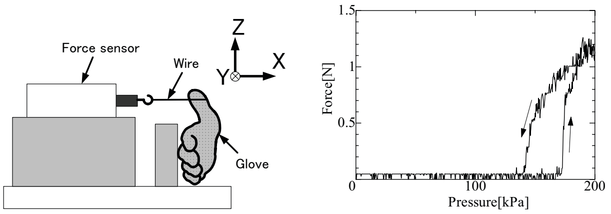
3.1. Output Force

Power-assist glove output characteristics were measured using the equipment in **Figs. 5(a)** and **(b)**, where changes in output at the index finger are measured while the glove assists flexion and extension. The force sensor maintains contact with the artificial muscle. The ini-



(a) Flexion (b) Extension

Fig. 6. Relationship between angle and force.



(a) Experimental equipment (b) Relation between angle and force

Fig. 7. Spiral rubber muscle.

tial state after the glove is attached is without force and pressure. Characteristics are measured while the finger is flexed from the initial state at flexion angles θ of 0°, 45°, and 90° in assisting flexion and at 45° and 90° in assisting extension. **Figs. 6(a)** and **(b)** show the relationship between force and pressure at each flexion angle.

The artificial muscle for flexion outputs 9 N at maximum when at a pressure of 200 kPa. Persons aged of $\geq$ 50 years average a finger pinching force of 43 N (men) or 38 N (women), so the glove assists flexion up to 20%. Fingers feel little pressure up to 170 kPa (dead-band) and show hysteresis at $\geq$ 170 kPa. The dead-band coming at the end at 170 kPa presumably results from the rapidly expanding rubber tube exceeding the preventive force by the cloth covering the tube. The tube returns to its original state by restitution when it depressurizes, creating hysteresis. The artificial muscle for flexion, when depressurized, extends the muscle under pressure, causing no problem from hysteresis. The artificial muscle for extension produces a force of 3 N up to 150 kPa at flexion angles of 45° and 90°, indicating that the angle has little effect. The dead-band extends to 70 kPa.

Output change at the finger is measured when the device assists opponens pollicis motion using the equipment in **Fig. 7(a)**. A wire on the thumb measures tensile force created by opponens pollicis motion. The state without force and pressure after the glove is attached is set at the initial state. **Fig. 7(b)** shows the relationship between force and pressure.

The spiral rubber muscle produces 1.2 N at the finger at 200 kPa, and a dead-band extends to 170 kPa, as with the sheet-like curved rubber muscle for flexion, showing hysteresis at a higher pressure presumably due to the same reason as for the artificial muscle for flexion. Hysteresis causes no problem for opponens pollicis motion because it operates as a toggle.

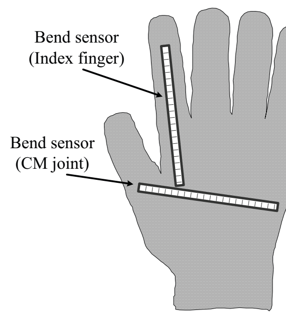
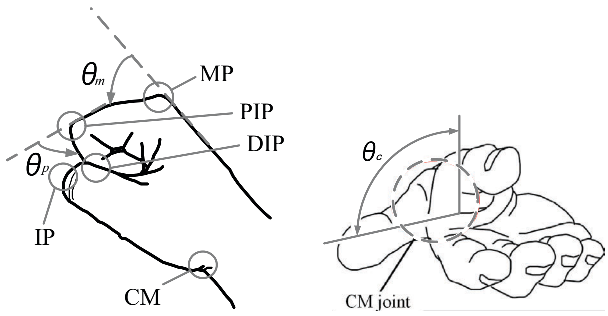


Fig. 8. Arrangement of bend sensor.



(a) Index finger (b) Definition of angle

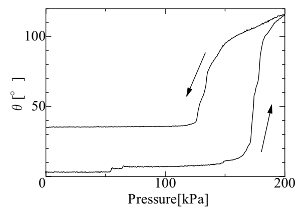
Fig. 9. Definition of angle.

3.2. Output Angle

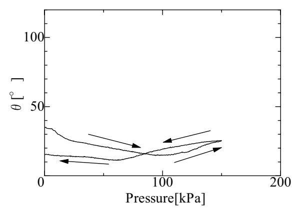
Flexion, extension, and opponens pollicis angles at the index finger are measured using a bend sensor (Abrams Gentile Entertainment) when the artificial muscle for the power-assist glove is pressed. Sensors on the glove, shown in **Fig. 8**, measure total angle θ of PIP joint angle θ_p and MP joint angle θ_m for the index finger (**Fig. 9(a)**) and adduction angle θ_c as of the opponens pollicis motion angle (**Fig. 9(b)**) [8].

The state without power after the glove is attached is set at the initial state. The artificial muscle is pressurized and depressurized to measure the index finger flexion angle. Artificial muscle for flexion, when depressurized, cannot be extended to a flexion angle of 0° by restitution alone. The artificial muscle is pressurized and depressurized to measure the extension angle reached by keeping the muscle for flexion constant. **Figs. 10(a)** and **(b)** show the measured index finger flexion and extension angles. **Fig. 11** shows the measured opponens pollicis angle.

The glove assists in index finger flexion and extension angles of 115° and 15° and opponens pollicis angle of 65°. An ordinary person has a movable total index finger MP and PIP range of 190° at the maximum and a shortfall of 75° with the glove. A movable range of 100° is sufficient for basic finger motion for daily living [9], confirming that the glove meets basic requirements. For the



(a) Flexion



(b) Extension

Fig. 10. Relationship between pressure and angle.

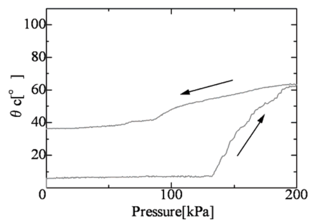
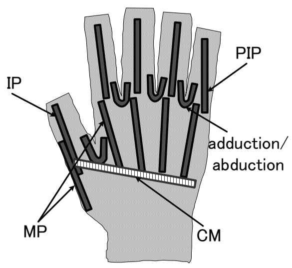


Fig. 11. Relationship between pressure and angle – CM joint.

(a) Overview



(b) Arrangement

Fig. 12. Data glove.

extension angle, the artificial muscle flexes opposite to extension at a pressure exceeding 100 kPa, so the maximum pressure for the artificial muscle for extension is 100 kPa. Fingers flex as an arch under normal conditions, and the muscle is not required to extend to an angle of 0°, and an extension angle of up to 15° will be sufficient. For the opponens pollicis motion angle, the movable angle range is 50° to 90°, and with an angle of 65°, the glove provides the desired assistance.

4. Control Using a Data Glove

4.1. Data Glove

A power-assist glove for assisting daily motion should adjust to the palm and back of the hand based on hand movement and the tools to be grasped. A data glove (5DT, Inc., 14Ultra) finds the finger target angle to realize the hand shape. **Fig. 12** shows the glove and sensor locations. The glove has 14 sensors for sensing flexion angles at the PIP and MP joints other than the thumb, IP and MP in the thumb, and adduction and abduction angles for individual fingers. The glove has a bend sensor for sensing of the opponens pollicis motion angle. Ten of the 14 sensors – excluding adduction and abduction angles – are used for control because the power-assist glove cannot assist adduction or abduction motion.

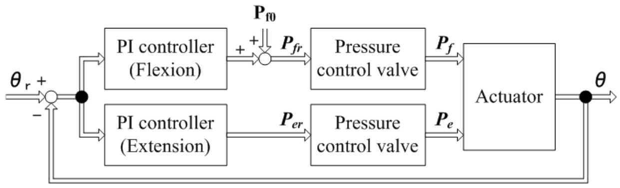


Fig. 13. Control.

4.2. Angle Control Using Total Finger Flexion Angle

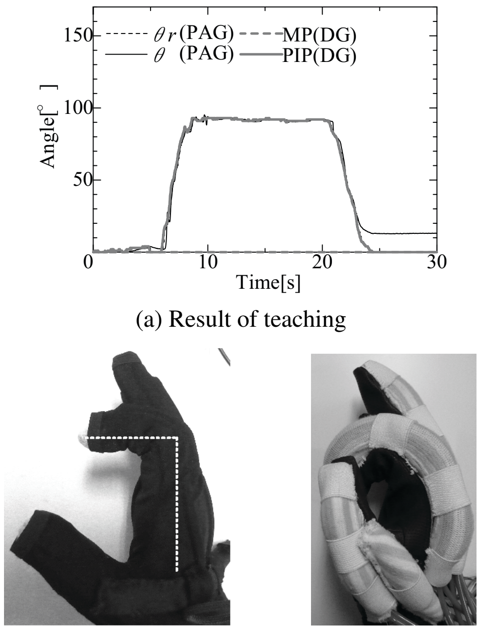
The power-assist glove used for finger motion having numerous freedoms at each joint requires numerous actuators to handle a complex structure, so a glove for assisting in daily living uses artificial muscle for 1 Degree Of Freedom (DOF) to reduce size and weight. Note that when the data glove is used to control muscles with one freedom, angles sensed by a glove having 2 sensors should be converted to that for a power-assist glove having one sensor.

This study proposes the following control: individual glove fingers have a bend sensor, as with the index finger, to control fingers by inputting target angles acquired by the glove to the power-assist glove. The target angle is the total angle at PIP and MP joints for fingers other than the thumb, and the total angle at thumb IP and MP joints. The artificial muscle for flexion and spiral rubber muscles are provided with an initial pressure of 100 kPa at working in assistance.

Figure 13 shows feedback control with angle control, wherein θ is the angle observed at the finger – PIP joint angle θ_p plus MP joint angle θ_m, in **Fig. 9(a)**, where θ_r is a target angle at the finger, P_f and P_e are inner pressure for artificial flexion and extension muscles. P_{fr} and P_{er} are target pressures in artificial muscles for flexion and extension, and f_0 is the initial pressure in artificial muscles for flexion. Control for opponens pollicis motion and initial pressure are similar to that the artificial muscle for flexion.

We conducted two experiments – one only flexing the PIP joint in the data glove to 90° and the other only flexing the MP joint to 90°. Responsiveness was measured at target angles acquired by the data glove as follows: the state without force after the finger is extended is set as the initial state. Inputting the target angle from the data glove to the power-assist glove is called "teaching" mode.

- 0 to 5 s: Keeping the initial state
- 5 to 20 s: Flexing fingers or grasping an object using fingers
- 20 to 30 s: Extending fingers to return to the initial state

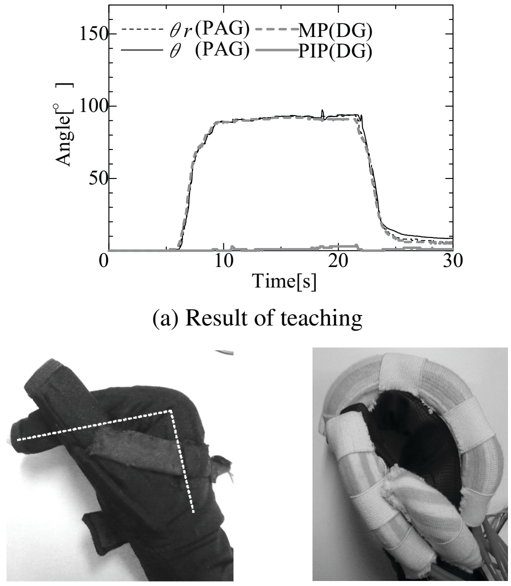


(a) Result of teaching

(b) Teaching mode

(c) Control mode

Fig. 14. PIP index.



(a) Result of teaching

(b) Teaching mode

(c) Control mode

Fig. 15. MP index.

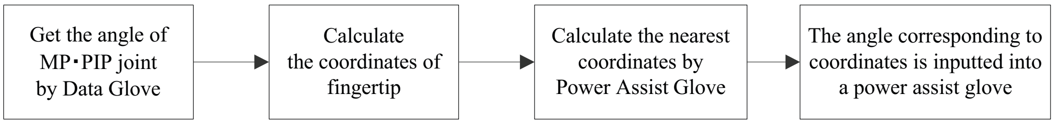


Fig. 16. Teaching algorithm.

Figures 14 and **15** show experimental results during teaching for the data glove and motion assistance for the power-assist glove, and give glove overviews. Finer broken lines denote target angles for the power-assist glove, finer solid lines measured angles for the power-assist glove, thicker broken line flexion angles for the MP joint during teaching, and thicker solid line flexion angles for PIP joints. As shown in **Fig. 14(a)**, finer broken lines (target angles at the power-assist glove), finer solid line (observed angles) and thicker solid line (flexion angles for the PIP joint during teaching) overlap. Similarly, the finer broken line (target angles for the power-assist glove), as do finer solid line (observed angles) and thicker broken line (flexion angles for the MP joint during teaching) overlap, as shown in **Fig. 15(a)**. The target angle for the power-assist glove is the sum of finger flexion angles sensed by the 2 sensors in the data glove, so the target angle sensed when MP and PIP joints are flexed at 0° and 90° is the same as that sensed when MP and PIP joints are flexed at 90° and 0°. The power-assist glove overview for the PIP joint is the same as that for the MP joint, despite teaching implemented under different conditions while the power-assist glove provides assistance as shown in **Figs. 14(c)** and **15(c)**.

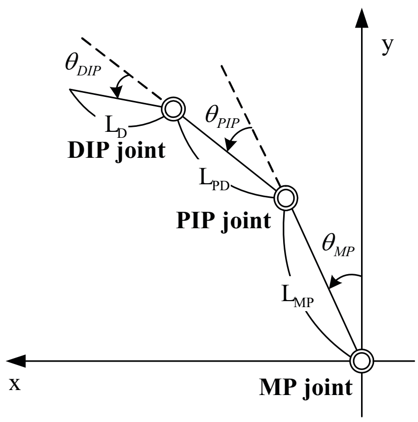


Fig. 17. Kinematical model of finger – data glove.

4.3. Control of Angles by Finger Coordinates

Target angles are found using the data glove finger coordinates to control the power-assist glove, to solve the above problems. **Fig. 16** shows the control algorithm. The target coordinates are calculated based on the MP and PIP joint angles acquired by the data glove. The angle for the position nearest to the finger coordinates is calculated, and it is inputted as the target angle to the power-assist glove.

As shown in **Fig. 17**, the MP joint is taken as the orig-

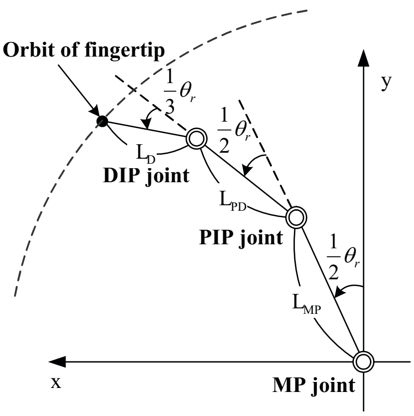


Fig. 18. Kinematical model of finger – power-assist glove.

inal point, wherein L_{MP}: distance between MP and PIP joints, L_{PD}: distance between the PIP and DIP joints, L_D: distance between the DIP joint and finger, θ_{MP}: flexion angle for the MP joint, θ_{PIP}: flexion angle for the PIP joint, and θ_{DIP}: flexion angle for the DIP joint.

The finger coordinates (x_t, y_t) of the data glove are given by Eq. (1), where θ_{DIP} is assumed to be equal to $\frac{2}{3}\theta_{PIP}$, because there is a proportional relationship of $\theta_{DIP} = \frac{2}{3}\theta_{PIP}$ [10].

$$\begin{aligned} x_{dt} &= L_D\cos(\theta_{MP}+\theta_{PIP}+\frac{2}{3}\theta_{PIP}) \\ &\quad +L_{PD}\cos(\theta_{MP}+\theta_{PIP})+L_{MP}\cos\theta_{MP} \\ y_{dt} &= L_D\sin(\theta_{MP}+\theta_{PIP}+\frac{2}{3}\theta_{PIP}) \\ &\quad +L_{PD}\sin(\theta_{MP}+\theta_{PIP})+L_{MP}\sin\theta_{MP} \quad . \ . \ (1) \end{aligned}$$

The target angle to be inputted to the power-assist glove is θ_r, and the target angle for each of the MP and PIP joints is $\frac{1}{2}\theta_r$ as of **Fig. 18**, assuming that these joints flex to the approximately same extent. Then, the coordinates of finger (x_t, y_t) when the target angle θ_r is inputted to the power-assist glove is given by Eq. (2), as is the case with finding the coordinates by the data glove assuming that the flexion angle for the DIP joint is assumed to be $\frac{1}{3}\theta_r$ based on the proportional relationship of $\theta_{DIP} = \frac{2}{3}\theta_{PIP}$.

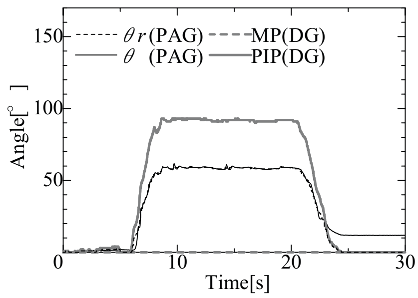
$$\begin{aligned} x_t &= L_D\cos(\frac{1}{2}\theta_r+\frac{1}{2}\theta_r+\frac{1}{3}\theta_r) \\ &\quad +L_{PD}\cos(\frac{1}{2}\theta_r+\frac{1}{2}\theta_r)+L_{MP}\cos\frac{1}{2}\theta_r \\ y_t &= L_D\sin(\frac{1}{2}\theta_r+\frac{1}{2}\theta_r+\frac{1}{3}\theta_r) \\ &\quad +L_{PD}\sin(\frac{1}{2}\theta_r+\frac{1}{2}\theta_r)+L_{MP}\sin\frac{1}{2}\theta_r \quad . \ . \ (2) \end{aligned}$$

Then, distance D between the coordinates (x_{dt}, y_{dt}) and coordinates (x_t, y_t) is found by Eq. (3), and the target angle θ_r that minimizes the distance D is found to control the power-assist glove angle.

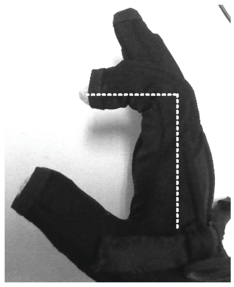
$$D = \sqrt{(x_{dt}-x_t)^2+(y_{dt}-y_t)^2} \quad . \ . \ . \ . \ . \ . \ (3)$$

The angle is controlled by the finger coordinates. The experiments are conducted in a manner similar to the angle control using the sum of flexion angles, where distance between the joints is adjusted to that of the subject.

Figures 19 and **20** show experimental results during teaching by the data glove and motion assistance by the power-assist glove, and overviews of the gloves. Finer



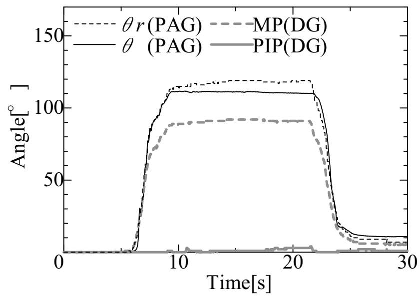
(a) Result of teaching



(b) Teaching mode

(c) Control mode

Fig. 19. PIP index.

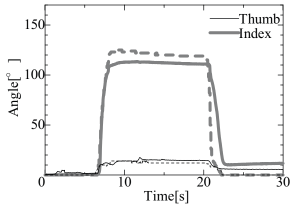


(a) Result of teaching

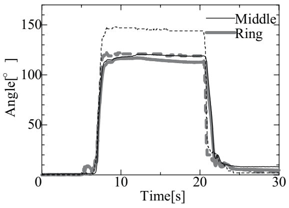
(b) Teaching mode

(c) Control mode

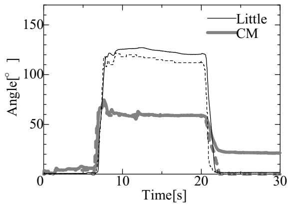
Fig. 20. MP index.



(a) Result of teaching (Thumb-Index)



(b) Result of teaching (Middle-Ring)



(c) Result of teaching (Little-CM)

(d) Teaching mode

(e) Control mode

Fig. 21. Grasping wooden rod.

broken lines denote target angles for the power-assist glove, finer solid lines measured angles for the power-assist glove, thicker broken lines flexion angles for the MP joint during teaching, and thicker solid line flexion angles at PIP joints. As shown in **Fig. 19(a)**, finer broken lines – target angles for the power-assist glove – and finer solid lines – observed angles – mutually overlap. Results and overviews in **Figs. 19** and **20** confirm that finger shape and location during teaching are more accurately reproduced than that obtained by controlling the angle with the sum of flexion angles for the finger (**Figs. 14** and **15**). When fingers grasp a tool, positions of fingers in contact with the tool are important, and the angle control using the finger coordinates is considered to be effective.

Figure 21 shows experimental results and overviews when a wooden rod (diameter: 22 mm) is grasped, wherein finer and thicker broken lines denote target flexion angles at the five fingers and opponens pollicis angle and finer and thicker solid lines denote observed flexion angles for the five fingers and opponens pollicis angle. As shown in **Figs. 21(b)** and **(c)**, thicker broken lines (target angles for fingers) and thicker solid line (measured angles for the fingers) overlap each other. As shown in **Figs. 21(d)** and **(e)**, the wooden rod is similarly grasped during the teaching and control periods, confirming that angle control by finger coordinates is also effective for grasping an object.

(a) 0 s (b) 1 s (c) 2 s (d) 4 s (e) 5 s

(f) 6 s (g) 7 s (h) 9 s (i) 10 s

Fig. 22. Continuous images.

4.4. Application Cases

Teaching is conducted for continuous motion using angle control (Section 4.3), where the power-assist glove works with the angle acquired 3 s before the data glove works as the target angle. The data glove is operated as follows:

- 0 to 2 s: Flexing all five fingers from the initial state
- 2 to 5 s: Keeping the flexed condition
- 5 to 7 s: Extending all five fingers
- 7 to 10 s: Maintaining extended conditions

Figure 22 shows overviews of the data glove and power-assist glove observed for 0–10 seconds, confirming that the data glove shape is reproduced by the power-assist glove in 3 seconds, as shown, for example, above in **Fig. 22(b)** and below in **Fig. 22(d)**, and above in **Fig. 22(c)** and below in **Fig. 22(e)**, and that proposed angle control by finger coordinates is also effective for continuous motion.

5. Control Using EMG

The hand shape is realized for each motion taught by the data glove, as discussed in Section 4. The glove wearer may, however, find it difficult to decide assistance timing. This section proposes control using EMG to enable the wearer to decide assistance timing.

5.1. Experiments in Controlling Finger Flexion and Extension

When a wearer's intent is to be understood using EMG, finger and opponens pollicis flexion/extension motion

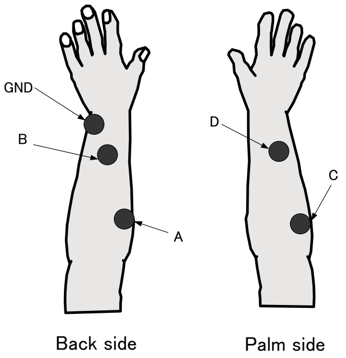


Fig. 23. EMG measurement point – left arm.

needs to be extracted from EMG to apply pressure to artificial muscles. Here we consider only finger flexion/extension, leaving opponens pollicis uncontrolled, to verify that EMG helps the wearer decide assistance timing. Outer muscles responsible for finger motion include the following:

- Finger flexion: flexor digitorum superficialis, interosseous, extensor carpi radialis, and extensor carpi ulnaris muscles.
- Finger extension: extensor digitorum, lumbrical, interosseous, flexor carpi radialis, and flexor carpi ulnaris muscles.

Interosseous and lumbrical muscles are in the hand and others in the forearm. Wearing power-assist glove, electrodes are attached to the forearm so that they do not interfere with user grasping or artificial muscles as when attached to the palm or the back of the hand. Measurement points are at the extensor carpi radialis muscle for finger flexion and extensor carpi ulnaris muscle for finger extension. These muscles are relatively easy to measure for glove control. **Fig. 23** shows electrode locations at the extensor carpi radialis muscle at Point A and extensor carpi ulnaris muscle at Point C. Points B and D are described later. A GND electrode at the ossis pisiformis, which has no muscle, is used for grounding.

Figure 24 shows the algorithm for controlling finger flexion/extension with t_v as time elapsing after valve-controlled pressurization or depressurization and t_s as sampling time. The target pressure is set if t_v is 2 seconds or longer and kept if t_v less than 2 seconds to prevent unintentional movement. The target pressure is set at 300 kPa for flexion and 0 kPa for extension at Points A and C when an integral EMG exceeds a threshold.

Pressure is measured for the following movement implemented using the above algorithm with the wrist steadied. The integral EMG interval and threshold are set at 1 s and 0.05 mV.

- 0 to 5 s: Keeping the condition without power
- 5 to 10 s: Flexing all five fingers from the initial state
- 10 to 15 s: Extending all five fingers

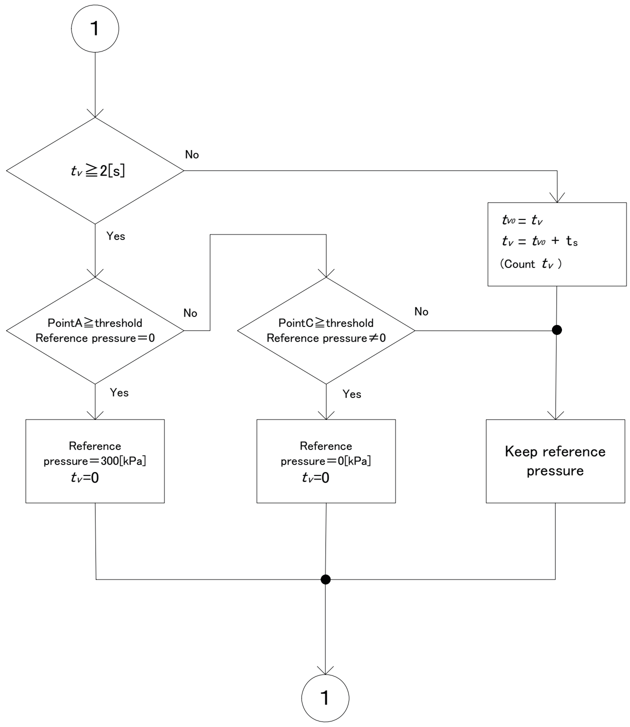


Fig. 24. Control algorithm.

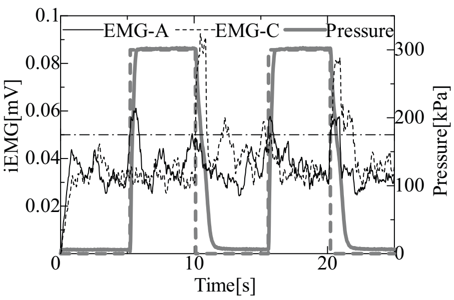


Fig. 25. EMG control results.

- 15 to 20 s: Flexing all five fingers from the initial state
- 20 to 25 s: Extending all five fingers

Figure 25 shows experimental results in which thicker broken lines denote the target pressure, thicker solid lines measured pressure, finer solid lines integral EMG at Point A, finer broken lines integral EMG at Point C, and dashed-dotted lines the threshold. The target pressure is set within 1 s after each flexion and extension, and pressure can be supplied to artificial muscles after determining finger movement from EMG using the algorithm. The above results are produced assuming that the wrist is steadied. The wearer's natural activity is hindered with the wrist steadied. The effects of wrist activity are discussed below.

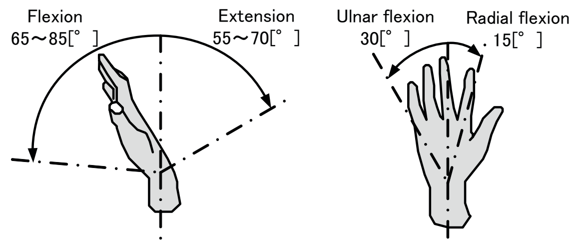
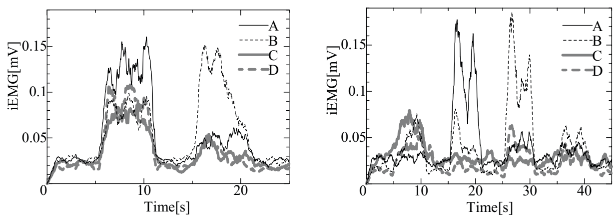


Fig. 26. Joint motion range.



(a) Finger motion (b) Wrist motion

Fig. 27. Experimental iEMG results.

5.2. Outer Muscles for Wrist Activity

Some of the outer muscles in Section 5.1 are also for wrist activity. **Fig. 26** shows 4 wrist movements and their ranges.

- Wrist flexion: flexor digitorum superficialis, flexor carpi radialis, flexor carpi ulnaris, and extensor carpi ulnaris muscles.
- Wrist extension: extensor digitorum, extensor carpi radialis, and extensor carpi ulnaris muscles.
- Wrist radial flexion: flexor carpi radialis and extensor carpi radialis muscles.
- Wrist ulnar flexion: flexor carpi ulnaris and flexor carpi ulnaris muscles.

The glove assisting daily living may cause serious problems such as dropping a grasped object in response to unintentional wearer wrist activity.

Distinguishing between finger and wrist activity was extensively studied to control myoelectric hand motion [11, 12]. Study results suggest the possibility of such distinction, but glove electrodes we developed should not interfere with glove activity.

Electrodes are attached to the extensor carpi radialis, extensor digitorum, flexor carpi ulnaris, and flexor digitorum superficialis muscles, which are relatively easy to measure given electrodes rarely interfering with glove activity and a combination of locations where finger and wrist activity are mutually distinguishable. **Fig. 23** shows locations of muscles electrodes are attached to, the extensor carpi radialis muscle (Point A), the extensor digitorum muscle (Point B), the flexor carpi ulnaris muscle (Point C), and the flexor digitorum superficialis muscle (Point D).

Whether finger and wrist movement can be mutually distinguished is verified by electrodes at these muscles.

5.3. Verification of Output Pattern

EMG is measured in 6 flexion/extension of the fingers and flexion/extension/radial-flexion/ulnar-flexion of the wrist to verify output differences.

Measurement is made individually for finger and wrist movement. For finger movement, EMG is measured as follows with the wrist steadied:

- 0 to 5 s: Keeping the powerless condition
- 5 to 10 s: Flexing all five fingers
- 10 to 15 s: Returning to a condition of no power
- 15 to 20 s: Extending all five fingers from the initial state
- 20 to 25 s: Returning to a condition of no power

For wrist motion, EMG is measured as follows with fingers steadied and all measurements made within the movable range:

- 0 to 5 s: Keeping the condition without power
- 5 to 10 s: Flexing the wrist
- 10 to 15 s: Returning to a condition without power
- 15 to 20 s: Extending the wrist.
- 20 to 25 s: Returning to a condition without power
- 25 to 30 s: Ulnar flexing of the wrist
- 30 to 35 s: Returning to a condition without power
- 35 to 40 s: Radial flexing of the wrist
- 40 to 45 s: Returning to a condition without power

Figure 27(a) shows integral EMG measurement results of finger activity. **Fig. 27(b)** shows integral EMG measurement results of wrist activity. Lines A to D denote integral EMG at Points A to D.

Assuming target timing to pressure artificial muscles to be 0.5 s after the movement, **Fig. 28** shows integral EMG relative to the maximum, consider to be 1, among those measured at the 4 measurement points. Numbers 1 to 6 on the abscissas correspond to flexion and extension of the fingers and flexion, extension, radial flexion, and ulnar flexion of the wrist.

As shown in **Fig. 28**, the finger extension (Number 2) and radial flexion (Number 5) have the same EMG as those measured at Points A and B, and are difficult to mutually distinguish. This means that these levels may cause erroneous glove activity. Those measured at Point D mutually differ. It is thus possible to mutually distinguish these movements when EMG is measured at Points A to D.

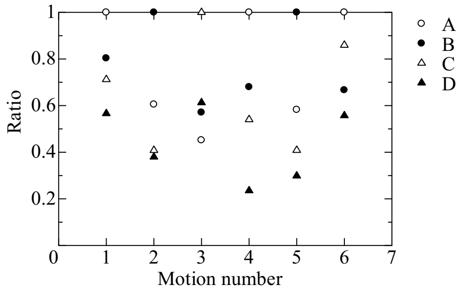


Fig. 28. iEMG ratio.

This confirms that the finger movement required for controlling the power-assist glove is extracted by using different output patterns of finger and wrist movement measured at the 4 points. We plan to develop ways to control the power-assist glove based on our study results.

Fingers and wrists are often used simultaneously used in daily life, e.g., drinking water in a PET bottle, combing hair. Mutually distinguishing between simultaneous finger and wrist movement is a question to be explored in projected work.

6. Conclusions

A power-assist glove made from sheet-like curved and spiral rubber muscles to enable flexion/extension of the fingers and opponens pollicis movement. The power-assist glove outputs 9 N maximum at the fingers for flexion at 200 kPa, showing that assists wearer pinching at 20%. We also developed a glove with an artificial muscle for individual fingers by finding finger shapes for daily activity by a data glove using finger coordinates. We also developed ways to control finger angles. We have realized pressure applied to artificial muscles using EMG when the glove is worn. Glove control while mutually distinguishing finger and wrist movement is left for future work.

The compact, lightweight, soft glove we developed is expected to be useful in assisting in daily activity and in rehabilitation of those who are paralyzed.

Acknowledgements

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