Extension Motion Assistance for Upper Limb Using Proxy-Based Sliding Mode Control

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***Abstract*—Many people of all ages have sustained cervical cord injury in traffic accidents, falls, or sport accidents, which has resulted in their physical impairment. Among such individuals, dysfunction of the upper limb is of particular concern, even though recovery from dysfunction is possible through rehabilitation. In this study, we developed a wearable assistive robot for the upper limb; this robot can be used to perform various tasks involving upper limb motion in daily life. To achieve this, we devised an algorithm for assisting extension motion. Individuals with C5-level Cervical Cord Injury (CCI) cannot perform extension of the elbow on their own. Therefore, we calculated the reference velocity curve and the angle of extension only from the force in the direction of flexion. In this way, the wearer can autonomously adjust the movement.**

***Index Terms*—Motion Assist Robot, Upper Limb, Extension Assist, Wearable Robot, Cervical Cord Injury**

I. Introduction

The number of people with disabilities increases every year. Although there are various functional disorders of the upper limb, two out of three cases of spinal cord injury (SCI) are caused by traffic accidents or falls. As one type of SCI, cervical cord injury (CCI) causes paralysis of the lower limbs and necessitates use of a wheelchair. Moreover, as the state deteriorates, the degree of paralysis worsens, and the upper limb is paralyzed sequentially starting from the hand. Recently, it has been reported that the number of new SCI cases is approximately 12,000 each year in the United States[1]. In Japan, meanwhile, the number of people with SCI has been estimated to be around 100,000, and individuals with CCI account for about 60% of all SCI cases.

CCI can occur if the cervical cord, which is a component of the central nervous system, is damaged by trauma to the cervical spine near the brain, which is located above the cervical vertebrae. The cervical spine contains eight cervical nerves (C1 to C8; see Fig. 1). For example, if C3 is damaged, spinal cord function at C4 and below might be lost, leading to paralysis. For reference, C5 controls the biceps brachii, C6 controls the extensor carpi, C7 controls the triceps brachii and flexor carpi, and C8 controls the digital extensor muscles. Therefore, in an individual with C6-level CCI, which is the most frequent of all eight types, force can be applied in the direction of flexion by the biceps brachii, while extension force cannot be applied by the triceps brachii. Being unable to extend the elbow interferes with a variety of activities of daily living, for example, pushing the body upward, supporting the weight of the body to prevent falling, and extending the arm over the head. Moreover, since the paralysis extends from the wrist toward the fingers, it is impossible to perform pronosupination of the wrist and bending and stretching of the fingers, which makes it difficult or impossible to grip objects. Also, there is no tactile sense in the forearm. Since the trunk cannot be controlled well, if the wheelchair is not inclined appropriately beforehand, the posture cannot be maintained. In having such a disorder, the ability to perform autonomous movements of the arms is severely limited. As a result, secondary disabilities such as joint contracture may arise. In such cases, if the triceps brachii can be assisted such that the patient can extend the elbow autonomously, the number of actions that the patient would be able to perform in daily life would increase considerably, which would naturally lead to improved Quality of Life (QOL).

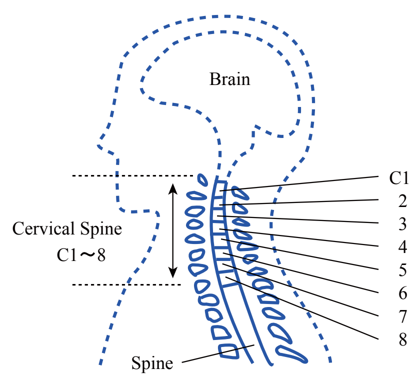


Fig. 1. Lateral view of spinal cord

Passive Range Of Motion Exercises (PROME) using continuous passive motion devices can prevent advancing joint contracture[2]. However, its effectiveness might be reduced if such rehabilitation is not performed during the acute phase. Recovery from joint contracture is difficult, and in some cases it might be impossible to continue the rehabilitation procedures if the locations and the time available for using rehabilitation devices are limited. Also, the patient might occasionally consider such training to be troublesome and inconvenient. Therefore, it is desirable to reproduce the effects of rehabilitation in daily life.

In recent years, wearable assistive robots have been successfully used to replace lost muscular power[3][4], and this type of technology is expected to become increasingly useful in daily life. However, mainly due to the large size of power assist systems, it is often difficult to introduce such devices into the daily life of patients. CCI patients are unable to use their hands, and therefore it is difficult for them to use large and inconvenient devices. Moreover, the operator cannot apply force in the direction in which they need assistance, which makes it difficult to control the necessary assistive force. Also, excessive reliance on a power assist system would prevent the patient from utilizing residual function, and in fact could lead to additional dysfunction.

In this study, feedback system is first reviewed with the aim that users with disabilities can wear and operate the system without unease and can maintain stable movement. In addition, since target patients with CCI cannot apply force in the direction of extension, we developed a system that supports natural extension by considering only motion in the direction of flexion. Specifically, we determined the parameters of extension motion when flexing the elbow to the maximum possible angle, which is rarely performed in daily life.

II. Active Cast for the Upper Limb

We developed a wearable robot with one degree of freedom (hereinafter referred to as Active Cast) as shown in Fig. 2, with the aim to provide a means of assisting disabled people with dysfunction of the upper limb. The Active Cast system was developed with long-term, user-friendly operation in mind, and it was designed to be as simple and lightweight as possible. Moreover, Active Cast does not restrict movements that are unrelated to the type of assistance it provides, such as pronation and supination of the forearm. Also, a special brace was designed considering the human skeleton.

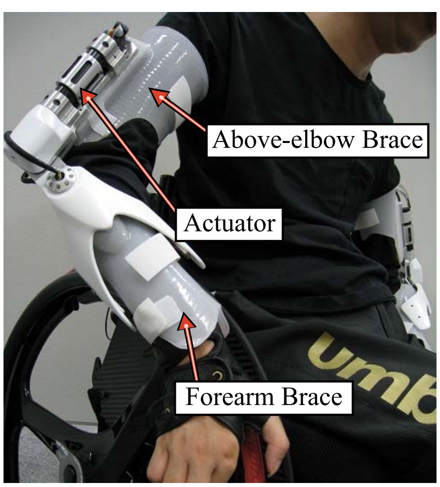


Fig. 2. Active Cast for the upper limb

A 50 [W] brushless DC motor was used as an actuator. By performing analysis with motion capture, it was determined that the specifications of the motor provided sufficient speed and unrestricted movement to the wearer. The maximum torque meets the requirements for operating a wheelchair, as obtained from simulations. Table I shows the specifications of Active Cast.

TABLE I
Specifications of the device

Nominal torque	5.6 [Nm]
Nominal speed	578 [deg/s]
Weight	850 [g]
Range of movement	135 [deg]

III. Control Design

Active Cast is controlled through the admittance controller based on input from pressure sensors placed at two positions on the forearm. The transfer function $G_A(s)$, which is an admittance controller of the mass damper system, is expressed as follows:

$$G_A(s) = \frac{1}{Ms^2 + Ds} \tag{1}$$

Here, M [kgm^2] is an inertia coefficient and D [Nms/deg] denotes variable viscosity, as shown in Eq. 2. The viscosity is changed depending on the angular velocity of the arm of the wearer $|\dot{\theta}_h|$ [deg/s]. The viscosity increases when the device stops and decreases when the device commences motion in order to improve its operation. Here, the initial viscosity D_s is set to 0.25 [Nms/deg], and the viscosity reduction factor A_D is set to 0.5 [-].

$$D = \frac{D_s}{\frac{|\dot{\theta}_h|}{A_D} + 1} \tag{2}$$

Signals from pressure sensors pass through a dynamic filter developed in this laboratory[5]. It is effective for reducing the input delay, and it is as efficient as a low-pass filter. Furthermore, T_d [s] is the time constant of the filter. The cutoff frequency of the filter is set as shown in Eq. 3. We consider that noise at the low cutoff frequency can be removed if T_d is much larger; however, in this case the response delay might increase since T_d is a time constant. f_{Dy} [V] is the input after passing through the LPF, which changes the time constant, and α [-] and β [-] are constants. In this study, we set α=1.01 and β=50.0.

$$\frac{1}{T_d} = \log_{10}(|\dot{f}_{Dy}| + \alpha) \times \beta \tag{3}$$

The motor driver controls the speed of the motor. The basic control system is as explained above. However, CCI patients have paralysis of the lower limbs and trunk, and so the device is worn on the arm and only motions that they can perform freely can be used to control the device. In this regard, it is necessary to ensure that the device can be operated safely by a user with disabilities. Therefore, we applied Proxy-Based Sliding Mode Control (PSMC) to Active Cast as a feedback method aiming to improve its operational safety. PSMC is a method proposed by Kikuuwe et al.[6]. A virtual object referred to as "proxy" is assumed to have no mass, and the method uses a sliding mode control for this proxy.

In order to confirm the effectiveness of PSMC, we conducted an experiment where the device entered an unstable state and we used proportional–integral–derivative (PID) control for comparison. In the experiment, we made the device halt abruptly after performing a quick extension. This type of motion creates an unstable state. The results of this experiment performed by using PID control are shown in Fig. 3, and the results obtained by using PSMC are shown in Fig. 4. In these graphs, the values from pressure sensors, the command signal to the motor and the angle of Active Cast are shown from top to bottom.

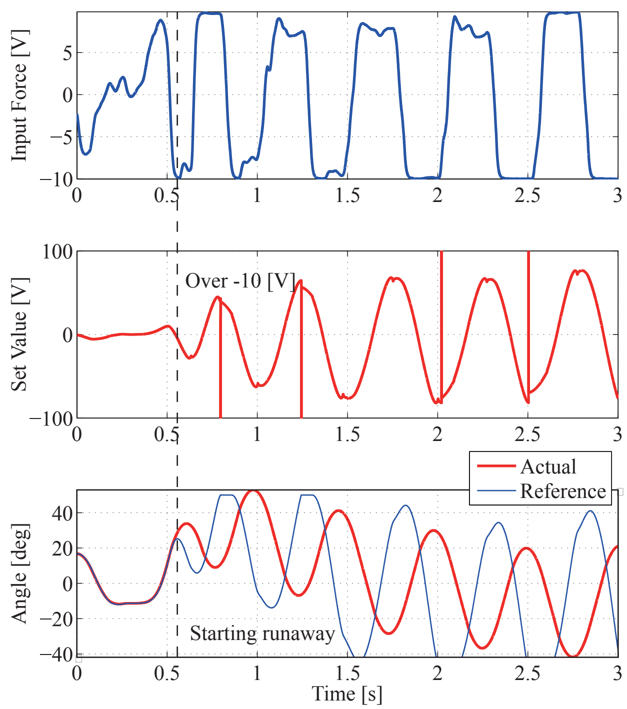


Fig. 3. Experimental results for Active Cast with PID control

We used a motor driver for control the set value, which was limited to ± 10 [V]. When utilizing system output saturation, it does not exceed the maximum output. With PID control, the state displayed vibration and went out of control after around 0.5 [s]. The reference value could not reach the actual angle, and the state did not converge. This is considered to be caused by the limited performance and output of the motor. Also, since the pressure sensors are constantly in contact, the device cannot enter a stable state with the arm at rest due to the presence of residual force. In contrast, with PSMC, when increasing the difference between the set value, which is limited, and the reference value, the device suspended its operation until the reference value approached the angle of the device. Thus, the unfavorable behavior disappeared even when the angle deviation increased. As seen above, in this experiment we obtained valid results for operation which can improve the operational safety of this device.

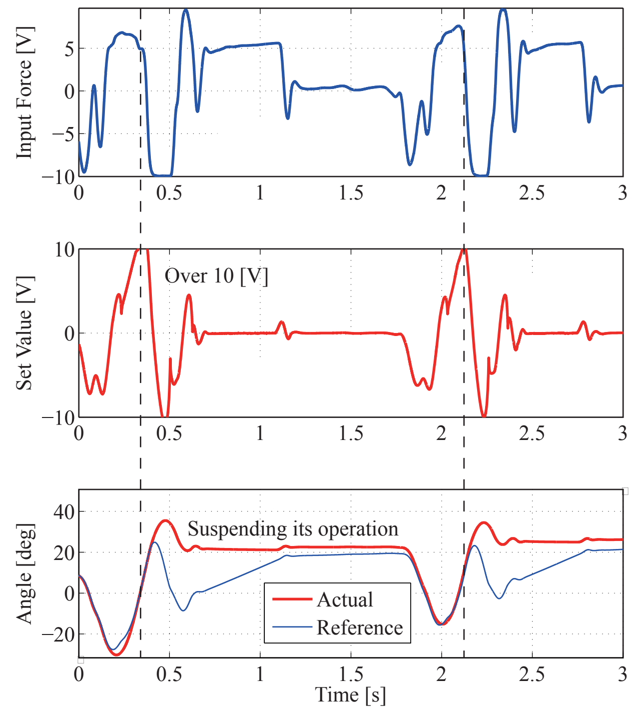


Fig. 4. Experimental results for Active Cast with proxy-based sliding mode control

IV. Assistance for Extension of the Elbow

A. Extension of a Raised Elbow from a Flexed State

Actions such as reaching for an object on a shelf or raising the arm to press an elevator button are difficult for C5-level CCI patients with paralyzed triceps brachii. Accordingly, we consider an assistance method for elbow extension which does not cause discomfort even if the elbow is raised above the level of the shoulder. If individuals with CCI attempt to extend the elbow while it is raised, they cannot defy gravity and can apply force only in the direction of flexion since no force can be applied in the direction of extension. As pressure sensors installed on Active Cast are placed within a narrow range in order to improve the sensitivity, the input soon becomes saturated. However, the elbow is rarely flexed to the maximum angle 130 [deg] in daily life. If the individuals don't have joint contracture, they can flex maximum. Therefore, Active Cast extends the elbow slowly and automatically, as shown in Eq. 4, when the wearer flexes the elbow to the maximum angle. If force is applied in the direction of extension during automatic motion, it can be canceled since it is considered that the elbow is below the shoulder. Here, f_{out} [V] is the value from the pressure sensors after it passes through the filter.

$$v = \begin{cases} 5 & (f_{out} \leq 0) \\ f_{out} G_A & (f_{out} > 0) \end{cases} \tag{4}$$

Since axis conversion in the robot is performed using a worm gear, information can be obtained only from the pressure sensors. However, by driving the motor slowly, changes in the current value of the motor can be obtained when load is applied in the opposite direction. This automatic operation is possible to within 5 [deg] from the maximum angle of flexion. In this interval, the wearer is able to adjust the magnitude of the force in the direction of flexion in order to determine the desired extension angle and speed. The angle and the speed of the device are calculated by measuring the accumulated value and the maximum differential value of the motor current. The extension angle is set to a larger value if greater force is applied continuously, and the velocity is increased if force is applied suddenly. This system is shown in Eq. 5. A_{max} is the criterion value of the maximum velocity of extension, A_{sum} is the criterion value of the reachable angle, A_{in} is the current value of the motor.

$$A_{sum} = A_{sum} + A_{in} \qquad (A_{sum} \leq L_{max}) \tag{5a}$$

$$A_{max} = max(\dot{A}_{in}) \qquad (A_{max} \leq V_{max}) \tag{5b}$$

A quadratic curve is used for the generated reference velocity curve. Until reaching a certain angle, the coefficients of the generated velocity curve are calculated by measuring the motor current value. At first, we obtain the maximum velocity during assisted motion, and Q_3 is determined as shown in Eq.6 by normalizing A_{max}. Here, V_N is the largest experimentally measured value, and V_{max} is the limited maximum velocity.

$$Q_3 = A_{max} \times \frac{V_N}{V_{max}} \tag{6}$$

Next, Q_2 is obtained from the intersection of the time axis and the reference velocity curve. The generated velocity curve should be $v = 0$ [deg/s] when the assistance mode begins at $t_0 = 0$ [s] since the motion begins from a static state. At this time, the left edge of the quadratic function must be placed at the origin, and the smaller solution for Q_2 should be 0.

$$\begin{aligned} -(Q_1 t + Q_2)^2 + Q_3 &= 0 \\ t &= \frac{-Q_2 \pm \sqrt{Q_3}}{Q_1} \\ \frac{-Q_2 - \sqrt{Q_3}}{Q_1} &= t_0 = 0 \\ Q_2 &= -\sqrt{Q_3} \end{aligned} \tag{7}$$

Finally, Q_1 is obtained from the relationship between the velocity curve and the attained angle. The attained angle after performing an assistance motion of L [deg] is determined as shown in Eq. 8 by normalizing A_{sum}, similarly to Eq. 6.

$$L = A_{sum} \times \frac{L_N}{L_{max}} \tag{8}$$

Here, Q_1 is calculated as shown in Eq. 9 since the distance can be calculated by integrating the velocity curve.

$$\begin{aligned} \int_0^{\frac{-Q_2+\sqrt{Q_3}}{Q_1}} \{-(Q_1 t + Q_2)^2 + Q_3\}\, \mathrm{d}t = L \\ Q_1 = \frac{-3Q_2Q_3 + 2Q_3\sqrt{Q_3} + {Q_2}^3}{3L} \end{aligned} \tag{9}$$

A summary of the calculation formulas for each factor is shown in Eq. 10. Respectively, Q_3 is the maximum velocity of the extension, Q_2 adjusts the curve to the origin, and Q_1 changes the arrival time. Note that Q_3 must be calculated first in order to calculate the remaining coefficients.

$$\begin{cases} Q_3 & = A_{max} \times \frac{V_N}{V_{max}} \\ Q_2 & = -\sqrt{Q_3} \\ Q_1 & = \frac{-3Q_2Q_3 + 2Q_3\sqrt{Q_3} + {Q_2}^3}{3L} \end{cases} \tag{10}$$

It has been shown that a bell-shaped velocity curve is more suitable for the velocity curve of an extension (reaching) movement of the arm[7]. In order to achieve this, the generated quadratic curve is passed through the LPF, which has a time constant of 0.2 [s], and the reference curve is approximated to the bell-shaped trajectory. The quadratic function is represented with the above constants as shown in Eq. 11.

$$v_r(t) = \frac{-(Q_1 t + Q_2)^2 + Q_3}{0.2s + 1} \tag{11}$$

In this study, based on the specifications of our equipment, the maximum velocity V_N was set to 200 [deg/s], and the maximum extension angle L_N was set to 95 [deg].

After extending the elbow in accordance with the reference curve, the motion is locked in the direction of flexion. The lock is released when force is applied in the direction of extension. In addition, since the current value of the motor is limited, the automatic assistance motion is stopped if the operation is blocked by obstacles.

B. Extension Assistance During Ordinary Motion

When the body is moved, the stiffness of the muscles is changed to match the speed and direction of movement[8][9]. Fine motor movement is enabled by increasing the stiffness by using the antagonistic muscle, especially in cases when fine-tuning is needed at low speeds. The antagonistic muscle is the muscle applying force in the opposite direction during movement. In the case of the upper limb, for example, triceps brachii applies force in the direction of extension when the elbow is extended, and the biceps brachii, as the antagonistic muscle, is used to adjust the velocity. However, since triceps brachii is paralyzed in C5-level CCI patients, who are the target of this study, extension can be achieved only by loosening the biceps and harnessing gravity, and smooth extension is difficult to achieve. Similarly, the triceps cannot function as the antagonistic muscle during flexion. We analyzed the extension of the elbow by using motion capture techniques, where the participant was a man in his 30s with C5-level CCI. In this experiment, we asked the participant to extend the elbow as slowly and smoothly as possible. Fig.5 shows the results.

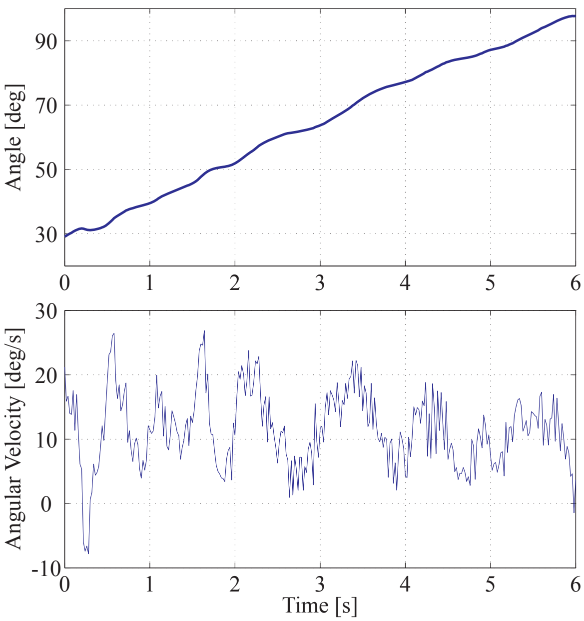


Fig. 5. Challenging an individual with C5-level CCI to extend the elbow slowly and smoothly

Slow and smooth extension should be performed at a constant speed; however, the results of this experiment show erratic movement. Moreover, the velocity curve occasionally approached 0 [deg/s], which indicates that the movement stopped at times. Thus, the participant could not apply force through the triceps brachii and could not extend his elbow smoothly.

For this reason, the assistive force is applied only during extension in normal operation. The formula used for calculating the amount of assistance is presented in Eq. 12.

$$f_a = (\frac{A_{in}}{0.5s+1} + K)(P + \frac{I}{s}) \qquad (12)$$

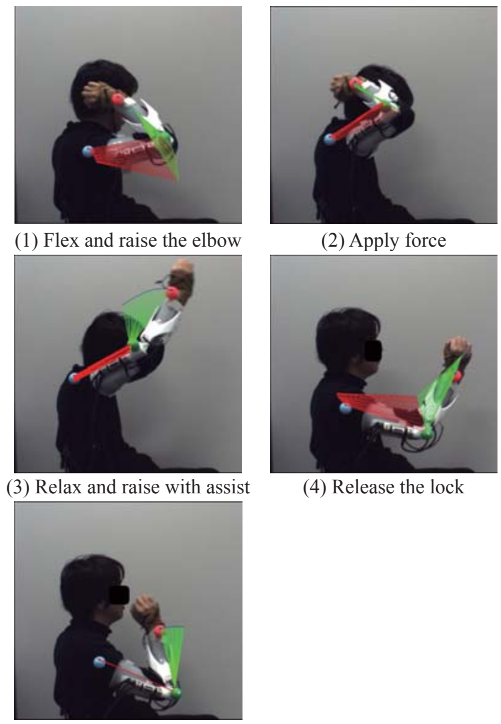
K, P and I are constants. As described above, by changing the assistive force based on the current A_{in} of the motor, the device is controlled to continue providing a constant load during extension. However, a sudden impact or sudden release of the load can cause discomfort for the operator. Therefore, the beginning and the end of the assistance operation are smoothened by applying a first-order lag function.

$$f = f_a \begin{cases} f_{Dy} + \frac{f_a}{0.5s+1} & (5 \leq \dot{\theta}_h) \\ f_{Dy} + \frac{0}{0.5s+1} \times \frac{1}{2} & (-5 < \dot{\theta}_h < 5) \\ f_{Dy} & (\dot{\theta}_h \leq -5) \end{cases} \qquad (13)$$

In the second column of this expression, it might appear that multiplication by 0 is meaningless. However, f_a remains when the operation is stopped after extending the elbow, and the role of this multiplication is to ensure that it slowly converges to 0.

V. Experimental Verification of Motion Assisted by Active Cast

We conducted an experiment using the developed Active Cast in order to verify the operation of the control method presented in this paper. The participant was a man in his 30s with C5-level CCI. His cervical nerves C6 and below are paralyzed, therefore, he cannot apply force in the direction of extention by trizeps brachii. The setup of the experiment is shown in Fig. 6. Colored lines represent trajectories of arm motion.



(1) Flex and raise the elbow
(2) Apply force
(3) Relax and raise with assist
(4) Release the lock
(5) Return to the original position

Fig. 6. Experimental setup with Active Cast for the upper limb

We asked him to perform the following sequence of actions while wearing the device.

1) Flex the elbow to the maximum angle and raise the elbow above the shoulder.
2) Apply force in the direction of flexion during automatic motion.
3) Relax and raise the arm with assisted extension.
4) Release the lock by stretching the elbow by utilizing gravity.
5) Return the arm to its original position.

In two consecutive series of operations, the first series was to be conducted slowly and for a short distance, while the second series was to be conducted rapidly and for a long distance. We analyzed the characteristics of the experiment by using motion capture. In order to perform measurements, we placed colored markers on the participant's shoulder, elbow, and wrist. After recording the motion at 50 [fps] with a color camera, we analyzed the positions of the color markers in three dimensions.

Fig. 7 shows, from top to bottom, the inputs from pressure sensors after they passed through the filter, the angle of Active Cast, the angular velocity of Active Cast, flag signals of the system mode and the relative displacement of each part relative to the Z axis. If the device is operateted freely, the flag signal output 0. When the flag signal is 1, it shows that the state is (2), the wearer is applying force in the direction of flexion. The device extend automatically when the flag signal is 2. If the lock is released after the extention, the flag signal is returned to 0. The extension movement is assisted in the shaded periods shown in the graph. The velocity curve has a bell-shape, and the joint angle increased smoothly during extension. During this period, the participant did not perform the extension by using his own muscles since the elbow was above the shoulder. In addition, the operation could be controlled by using only force that the participant could exert. Thus, by using the residual function effectively with the aid of Active Cast, the participant was able to compensate for lost function of the upper limb, and the results show that the proposed method is effective.

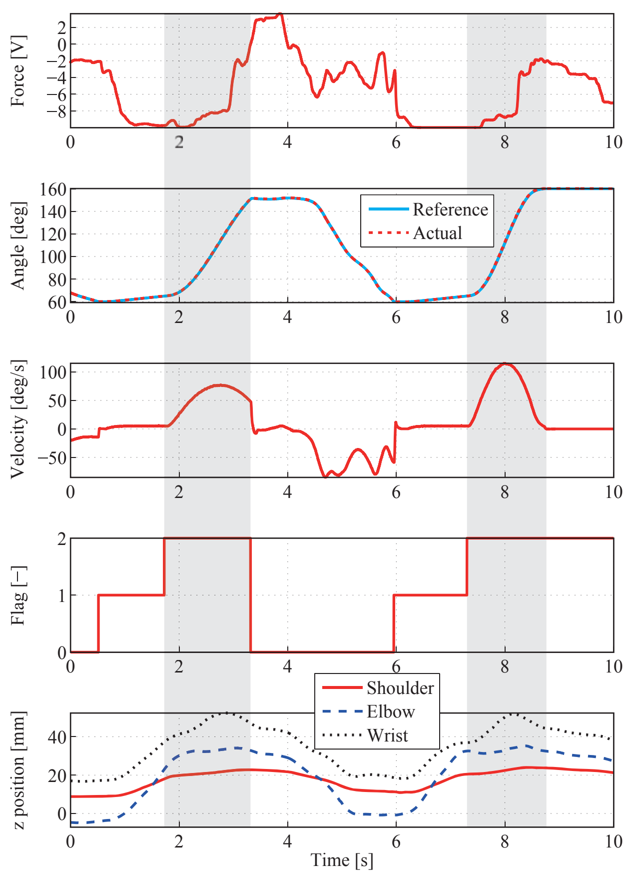


Fig. 7. Experimental results for assisted extension with Active Cast for the upper limb

VI. Conclusion

In this study, we targeted the problem of extension of the elbow for individuals with C5-level CCI. Although people with C5-level CCI and consequent upper limb dysfunction cannot exert force in the direction of extension, they can adjust the force in the direction of flexion to a certain extent. Therefore, assistance for extension was successfully implemented by adjusting the force in the direction of flexion. The time of commencing the assistance was set when flexing the elbow to the maximum angle, which is rarely performed in daily life. Finally, by implementing Active Cast in tandem with the proposed control method, we were able to assist the adjustment of the extension motion even in situations where the participant could not apply any force in the direction of extension.

In this experiment, the elbow was extended in such a way as to raise the arm above the shoulder. However, the proposed method is not limited to this type of motion, and it can be utilized with equal success in situations such as extending the elbow to the side or pushing a door open. Active Cast is based on the philosophy that the device only operates if the user needs assistance in daily living. Therefore, a method should be carefully devised in order to provide support for a variety of situations while ensuring that the device does not start to operate when not needed.

Acknowledgment

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