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A Wheelchair Operation Assistance Control for a Wearable Robot Using the User's Residual Function

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***Abstract*—Cervical Cord Injury (CCI) is a dysfunction of the upper limb. In an individual with C5-level CCI, which is the most frequent of all eight levels, force can be applied in the direction of flexion by the biceps brachii, but extension force cannot be applied because of the triceps brachii paralysis. Persons with C5-level CCI therefore cannot operate a wheelchair up an incline and over carpet. In this study, we estimated the wheelchair velocity during elbow flexion depending on the angular velocity of the elbow. A wearable assistive robot can assist with the elbow extension movement using this estimated velocity while the wheelchair is being operated.**

I. INTRODUCTION

The number of disabled person has been increasing every year. The disabilities include various kinds of dysfunctions of the upper extremities. Two-thirds of spinal cord injuries are caused by traffic accidents or a fall from a high altitude. Individuals with a cervical cord injury are forced to use a wheelchair because their inferior limb is paralyzed. In addition, their trunk and upper limbs, including their fingers, can become paralyzed as their condition worsens. In recent years, the U.S. has estimated that there are about 12,000 generating cases of spinal cord injury every year[1].

In an individual with a C5-level cervical cord injury (CCI), force can be applied in the direction of flexion by the biceps brachii muscle, but extension force cannot be applied because of the triceps brachii muscle paralysis. For this reason, many activities of daily living (ADL) are impossible for these individuals. For example, if they fall, they can't stand up again because they can't push up using their arms and support their body. They have a difficult time operating a wheelchair because they cannot hold the rims of the wheels. This makes it extremely difficult or impossible for them to wheel over a carpet and up a slight incline. Their fields of activities are smaller than the usual wheelchair user. Their self-reliance is reduced, and they are unable to exercise the paralyzed arm. Contracture of the joint may occur and pose a secondary obstacle to their mobility. If extension of the affected arm can be achieved by assisting the triceps brachii, then more activities of daily living can be performed, improving the individual's QOL. Improved QOL leads to self-reliant motion and helps prevent of a secondary obstacle.

By continuous transitive movement of a joint using CPM (Continuous Passive Motion) equipment([2], [3]), arthrogryposis and decreased ROM (Range Of Motion) can be prevented. With the use of CPM equipment, it is possible to achieve early rehabilitation and inhibit secondary obstacles from occurring. However, it may be difficult to continue rehabilitation if the patient can only use such apparatus in rehabilitation centers and use it for a limited time. Some patients are not motivated to train on CPM equipment under these circumstances. Therefore, it is desirable for rehabilitation to be done naturally, rather than in a special facility, and as a part of everyday life. It is desired that support robot of the wearing type is substituted to the muscular power which self-lost and can be used for various daily living ([4], [5]). However, many such whole body wearable type robots calculate the quantity of assistance need by the value from myoelectric potential and pressure sensor. It is therefore difficult to use these robots to someone with CCI who has paralyzed nerves.

Regarding the wheelchair operation, an operation analysis of a manual wheelchair is performed([6], [7]). There has also been research on power assisted wheelchair s equipped with a motor ([8], [9]). However, this kind of wheelchair cannot detect how the user operates the wheelchair, and does not make use of the residual function of a disabled person. In addition, when a manual wheelchair is remodeled into a powered wheelchair, the portability is reduced, as such wheelchairs can't be put into a regular passenger car.

In this study, we develop a wearable assist robot for the upper limb, called the Active Cast, which can assist in 1 DOF of the elbow. In addition, we develop a wheelchair operation support system considering the residual function. The research subject is a patient with C5 level CCI. This system assists only during the extension motion of the elbow, and not during the flexion motion. We estimated the parameters which could not be measured, such as the position of the hand and the angle of the shoulder from the position in relation to the body and wheelchair. The wheelchair velocity is also estimated by the calculation.

II. WEARABLE ROBOT

A wearable 1 axis type robot was developed to support of disabled persons with upper limb dysfunction. This robot is shown in Fig.1. The wearable robot developed in this research was designed for prolonged use and operability.

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Fig. 1. Wearable robot for the upper limb

The input in the control is a pressure sensor installed in the forearms (Fig.2). The forearm is a double structure composed of inner part and outer part. The inner part can be moved freely. Because the pressure sensor is sandwiched between the inner part and the outer part through the flat spring, the sensor is able to detect the wearer's motion for flexion and extension. In Figure 2, θ_{m} is the joint angle of the outer part and θ_{h} is the angle of the wearer's arm.

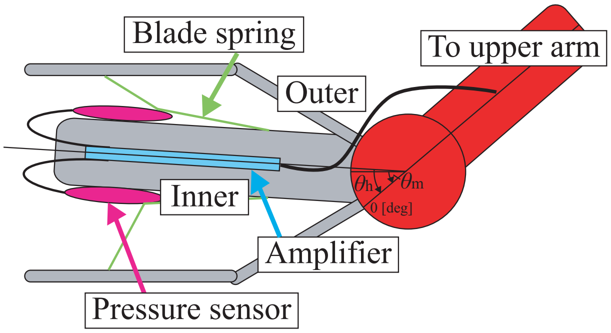

Fig. 2. Structure of forearm part of wearable robot

A brush less DC 100W motor was used as the actuator. Concerning the specifications, a healthy person's movements were analyzed by motion capture as an exploratory experiment. The robot was designed with the working speed that does not inhibit the wearer's movements. In addition, the maximum torque which can occur satisfies the torque which is needed for wheelchair operation obtained from the simulation. The specifications of the wearable robot developed in this research are shown in Table I.

TABLE I. SPECIFICATIONS OF THE DEVICE

Weight	830 [g]
Nominal output	100 [W]
Nominal torque	5.26 [Nm]
Nominal speed	475 [deg/s]
Range of movement	135 [deg]

An allowance of about 8.0 [deg] is designed in the direction of adduction and abduction of the front arm in order not to encumber the motion of the frame of the front arm in the joint axis. Therefore, a wrinkle that develops in the front arm the motion of the radius and ulna and that of adduction can be smoothedned out. We developed a special orthosis which is a part of the frame that adheres to the human body. The structure of the orthosis is a dual structure of both soft and hard material. The soft material is for fitting, and hard material for power transmission. The operability of the robot can be enhanced by designing it to match the wearer's physique.

III. CONTROL SYSTEM DESIGN

The wearable robot developed in this research is controlled by an admittance controller based on the information from the pressure sensor attached to the front arm. The transfer function $G_{\mathrm{A}}(s)$ is the admittance controller of the spring mass damper system as (1).

$$G_{\mathrm{A}}(s) = \frac{1}{Ms^2 + Ds + K} \tag{1}$$

where M is the inertia coefficient[kgm^2], D is the viscosity coefficient[Nms/deg], and K is the stiffness coefficient[Nms/deg]. In addition, D and K are the variability. D is represented by (2).

$$D = \frac{D_{\mathrm{I}}}{\frac{|\dot{\theta}_{\mathrm{h}}|}{A_{\mathrm{D}}} + 1} \tag{2}$$

where D_{I} is the initial viscosity coefficient[Nms/deg], A_{D} is the viscosity decrease ration[-], and $|\dot{\theta}_{\mathrm{h}}|$ is the angular velocity of the wearer's arm[deg/s]. $|\dot{\theta}_{\mathrm{h}}|$ is represented by (3). f_{in} is the input from the pressure sensor after passing the filter[V] and is obtained for the joint angle of the free motion of the inner part to an outer part in the front arm dual structure of the wearable robot using the constant A_{h}. Although the input of the pressure sensor is nonlinear, note that it is treated linearly in this research.

$$\dot{\theta}_{\mathrm{h}} = \frac{(f_{\mathrm{in}}A_{\mathrm{h}} + \theta_{\mathrm{m}})s}{T_{\mathrm{h}}s + 1} \tag{3}$$

The wearer's elbow joint angle is the sum of the angle of the inner part and the joint angle of the outer part θ_{m}. The joint angular velocity is obtained by derivation of the wearer's elbow joint angle. However, since signal noise becomes large, it passes the low pass filter of the first order leg of the time constant $1/T_{\mathrm{h}}$. D is changed depending on the angular velocity of a wearer's arm $|\dot{\theta}_{\mathrm{h}}|$[deg/s]. Therefore, operability is improved by increasing viscosity when the arm stops moving and decreasing it when the arm begins to move. In this research, A_{h}=0.75, T_{h}=0.01, D_{I}=0.6, A_{D}=50, M=1/25000. The angular limitation is set from the software and hardware for safety. The robot can only perform extension and flexion at a fixed angle. When the arm reaches the angle limit whether in flexion or extension, the motor is rapidly suspended, and the output and load becomes momentarily large. The virtual spring is set at each termination point in order to reduce the load of the motor. It is represented by (4) and (5).

$$K(\theta) = K_{\mathrm{max}} \times \frac{A_{\mathrm{sp}}(\theta)}{A_{\mathrm{lg}}} \tag{4}$$

$$A_{\mathrm{sp}} = \begin{cases} \theta_{\mathrm{m}} + A_{\mathrm{lg}} & (\theta_{\mathrm{m}} \geq -5.0) \\ 0 & (-5.0 > \theta_{\mathrm{m}} > -115) \\ \theta_{\mathrm{m}} + (120 - A_{\mathrm{lg}}) & (-115 \geq \theta_{\mathrm{m}}) \end{cases} \tag{5}$$

The motion angle of the robot is taken as a positive value in the expansion direction and set from -120[deg] to 0.0[deg], which is the maximum expansion. In this research, $K_{\max} = 4.0$, $A_{\mathrm{lg}} = 5.0$ where $K_{\max}$ is the maximum value of input from the pressure sensor; A_{lg} is a range to which a virtual spring reacts.

IV. ASSISTANCE CONTROL OF WHEELCHAIR OPERATION

A. Estimation of Shoulder Angle and Hand Position

In this section of the paper, we will describe how the wearable robot offers wheelchair operation support. It is possible for the robot to assist the person by obtaining the ideal velocity and the ideal torque according to the wearer's motion and moving the robot. Sasaki and others ([10], [11]) were able to calculate the hand power at wheelchair operation by using a control force ellipse, and searching for the pattern and the characteristic of the power change. However, such a calculation method has to measure the joint torque, because such a calculation method is profoundly affected by the joint torque performed by the operator. It is difficult to easily measure.

In this research, a method of assist control based on velocity control was proposed in order not to have to consider the joint torque which is performed by an operator and the change of the load for gravity at a slope. For simplicity of installation and for compactness, only the minimum necessary sensor was attached to the wearable robot. The wearable robot can only obtain information on the angle of the elbow needed for the human wearing it to move. If it is necessary to determine the support power needed according to the operation state of wheelchair then it is necessary to calculate the hand position and shoulder angle. The robot estimates the condition of the wheelchair by using the parameter fixed by subject and the change of the angle of an elbow.

In this research, the rigid model was composed of two links forming the upper arm and a front arm, and has two degree of freedom of a shoulder joint and an elbow joint as Fig.3. This model was calculated on the xy coordinates which are centered on the shoulder joint. In this model there is no motion of the shoulder. If it is possible to operate wheelchair in ideal conditions, only sagittal plane is calculated because the elbow cannot move in horizontal plane.

Then, the distance from the shoulder to the hand is determined uniquely by the angle of the elbow. Because the trunk is paralyzed, it is rare for the upper body of an individual with CCI to move when operating a wheelchair. By drawing the circle which is centered on this shoulder joint, an end point position was calculable to intersect with the circle of the rim of a wheelchair. First, the direct distance from the shoulder to the hand L_{12}[m] is calculated as (6). θ_2[deg] is the elbow angle obtained from the robot. In this paper, it is written as $\cos\theta_{\mathrm{i}} = \mathrm{C}\theta_{\mathrm{i}}$, $\cos(\theta_1 + \theta_2) = \mathrm{C}\theta_{12}$. And $\sin\theta_{\mathrm{i}}$ is similarly written as $\cos\theta_{\mathrm{i}}$.

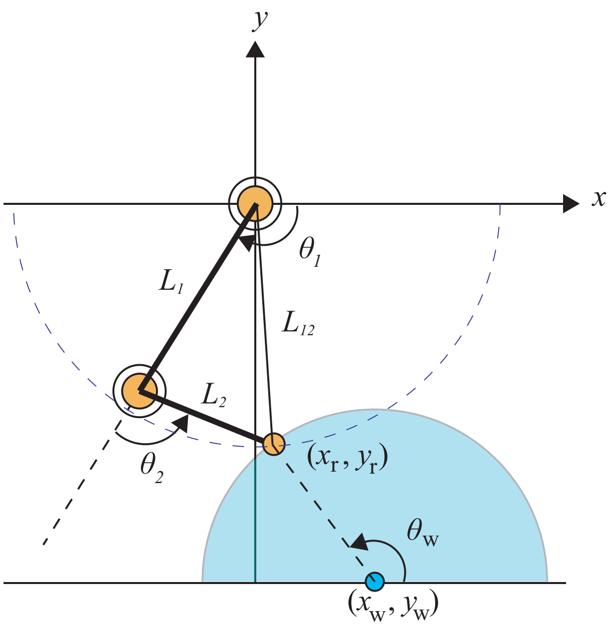

Fig. 3. Estimating hand's position from the elbow angle

$$L_{12} = \sqrt{(L_1 + L_2\mathrm{C}\theta_2)^2 + (L_2\mathrm{S}\theta_2)^2} \tag{6}$$

This is the radius of the circle which is centered on the shoulder joint. The simultaneous equation as (7) is set up for calculating the point at the intersection of this circle with the circle of the rim which is centered on the wheel of the wheelchair. x_{w}[m] and y_{w}[m] is the position of the rim's rotating center in the xy coordinate from the shoulder joint. r_{w}[m] is the radius of the rim.

$$\begin{cases} x^2 + y^2 = L_{12}^2 \\ (x - x_{\mathrm{w}})^2 + (y - y_{\mathrm{w}})^2 = r_{\mathrm{w}}^2 \end{cases} \tag{7}$$

(8) is a solution of this simultaneous equation by adding the above two equations. (9) is an equation which converted each coefficient of the equation (8) into O_1, O_2 and O_3. The equation of the line which connects the intersection of two circles is obtained.

$$x_{\mathrm{w}}x + y_{\mathrm{w}}y - \frac{x_{\mathrm{w}}^2 + y_{\mathrm{w}}^2 + L_{12}^2 - r_{\mathrm{w}}^2}{2} = 0 \tag{8}$$

$$O_1 x + O_2 y - O_3 = 0 \tag{9}$$

(9) is substituted to (7) with a coefficient replaced. (10) is obtained by computing the xy coordinates of the intersection point. $(x_{\mathrm{r}}, y_{\mathrm{r}})$ is the position of the hand in the xy coordinate system of the model.

$$\begin{cases} x_r = \frac{O_1 O_3 \pm O_2\sqrt{-O_3^2 + O_2^2 L_{12}^2 + O_1^2 L_{12}^2}}{(O_1^2 + O_2^2)} \\ y_r = \sqrt{L_{12}^2 - x_r^2} \end{cases} \tag{10}$$

Because (10) is the solution of the quadratic equation, x_{r} is found at both the positive and negative value. An intersection point of the circle is obtained one or two point. From characteristic features of wheelchair, the point nearer to the shoulder side is hand position during flexion movement of elbow and the point nearer to the center of rim is hand position during extension movement of elbow. About the sign of the second term of this numerator side of (10), since it has a negative value in xy coordinate system from $O_2 = y_{\mathrm{w}}$, a plus side is used during flexion of elbow and a minus side is used during extension of the elbow. If the hand position $(x_{\mathrm{r}}, y_{\mathrm{r}})$ can be known, then the shoulder joint θ_1[deg] can be calculated from (11) from the relation of inverse kinematics.

$$\theta_1 = -\sin^{-1}\left(\frac{L_2\mathrm{S}(\theta_2)}{\sqrt{x_{\mathrm{r}}^2 + y_{\mathrm{r}}^2}}\right) - \tan^{-1}\left(-\frac{y_{\mathrm{r}}}{x_{\mathrm{r}}}\right) \tag{11}$$

When operating the wheelchair, the hand has to move to the direction of rotation while the hand applies a load to the rim. Therefore, the velocity which directs the inside for the direction of the tangent of a rim is needed for a hand. This angle is obtained by (12) as $\theta_{\tan}$[deg].

$$\theta_{\tan} = \tan^{-1}\left(\frac{x_{\mathrm{r}} - x_{\mathrm{w}}}{y_{\mathrm{r}} - y_{\mathrm{w}}}\right) - \frac{\pi}{2} - \frac{\pi}{15} \tag{12}$$

By using the calculation above, it is possible to calculate the parameter needed to operate the wheelchair only by the motion of the elbow. For example, a hand's tangent angle to a rim can be calculated, as can the hand position on the rim, the angle of a shoulder joint, etc.

B. Estimation of Wheelchair Velocity

To achieve velocity control, it is important for the present velocity of the wheelchair to be precisely detected. The elbow moves according to the wheelchair velocity, and acceleration is then necessary in order for assistance to occur. Using the parameter that is computed here, the velocity of the wheelchair was estimated. When computing the wheelchair velocity using the forward kinematics, the equation is represented as the equation (13).

$$J\begin{bmatrix}\dot{\theta}_1\\ \dot{\theta}_2\end{bmatrix} = \begin{bmatrix}v_{\mathrm{w}}\mathrm{C}\theta_{\mathrm{tan}}\\ v_{\mathrm{w}}\mathrm{S}\theta_{\mathrm{tan}}\end{bmatrix} \tag{13}$$

where J is the Jacobian matrix and calculated by (14).

$$J = \begin{bmatrix}-(L_1\mathrm{S}\theta_1 + L_2\mathrm{S}\theta_{12}) & -L_2\mathrm{S}\theta_{12}\\ L_1\mathrm{C}\theta_1 + L_2\mathrm{C}\theta_{12} & L_2\mathrm{C}\theta_{12}\end{bmatrix} \tag{14}$$

It is possible to obtain the wheelchair velocity v_{w} from (13), $\dot{\theta}_1$ uses the derivative value and becomes very unstable. This result is expected since the angle of the shoulder joint is impossible to directly measure. Therefore, $\dot{\theta}_1$ is taken off from the calculus equation.

$$J^{-1} = \frac{1}{L_1L_2\mathrm{S}\theta_2}\begin{bmatrix}L_2\mathrm{C}\theta_{12} & L_2\mathrm{S}\theta_{12}\\ -(L_1\mathrm{C}\theta_1 + L_2\mathrm{C}\theta_{12}) & -(L_1\mathrm{S}\theta_1 + L_2\mathrm{S}\theta_{12})\end{bmatrix} \tag{15}$$

Using this, the Jacobian matrix is moved like (16) and $\dot{\theta}_2$ is obtained.

$$\begin{bmatrix}\dot{\theta}_1\\ \dot{\theta}_2\end{bmatrix} = J^{-1}\begin{bmatrix}v_w\mathrm{C}\theta_{tan}\\ v_w\mathrm{S}\theta_{tan}\end{bmatrix} \tag{16}$$

$\dot{\theta}_2$ is obtained by (16) and (17) is obtained by resolving v_{w}. An uncertain term like $\dot{\theta}_1$ disappears from the equation and it becomes possible to calculate the velocity of the wheelchair only by the parameters obtained.

$$\hat{v}_{\mathrm{w}} = \frac{\dot{\theta}_2 L_1 L_2 \mathrm{S}\theta_2}{-\mathrm{C}\theta_{tan}(L_1\mathrm{C}\theta_1 + L_2\mathrm{C}\theta_{12}) - \mathrm{S}\theta_{tan}(L_1\mathrm{S}\theta_1 + L_2\mathrm{S}\theta_{12})} \tag{17}$$

Approximation to a straight line linear expression is performed by the least-squares method expressed to equation (18) using the estimated wheelchair velocity and it is assumed that the wheelchair is operated with fixed acceleration. Although the velocity can be approximated by a curved line in flatland, a curved line cannot be determined by the physical power of the operator when the wheelchair is operated in places with a large load, such as a slope.

$$\begin{aligned} y &= P_1x + P_2\\ P_1 &= \frac{\sum_{k=1}^{n} x_k y_k - \sum_{k=1}^{n} x_k \sum_{k=1}^{n} y_k}{n\sum_{k=1}^{n} x_k^2 - (\sum_{k=1}^{n} x_k)^2}\\ P_2 &= \frac{\sum_{k=1}^{n} x_k^2 \sum_{k=1}^{n} y_k - \sum_{k=1}^{n} x_k y_k \sum_{k=1}^{n} x_k}{n\sum_{k=1}^{n} x_k^2 - (\sum_{k=1}^{n} x_k)^2} \end{aligned} \tag{18}$$

V. ELBOW MOTION SUPPORT CONTROL FOR WHEELCHAIR OPERATION

A. About Control Method

The method of application for the wearable robot is explained by the calculation method described above. Controlling the support was performed by dividing the types of support into the following four stages.

- phase 1 : the wheelchair operation by flexion
- phase 2 : preparatory phase until extension after flexion
- phase 3 : extension phase of elbow
- phase 4 : after extension support

Phase 1 is a flexion motion and is the stage in which the robot does not interfere with the user. Therefore, the robot performs motion to track the wearer's arm (19).

$$\theta_{\mathrm{m}} = f_{\mathrm{in}}G_{\mathrm{A}} \tag{19}$$

The velocity and acceleration of the wheelchair is estimated using equation (6)-(18). After the end of the flexion motion, a preparatory phase occurs. The phase consists of pushing the arm using the shoulder. In phase2, the baseline of pressure sensor transitions in such a way that the low limit of the pressure sensor f_{min} (maximum value with regards to direction of flexion) is zero. That is, the minimum of a pressure sensor f_{min} is subtracted from the input value of the pressure sensor f_{in}. In this way, the outer part of a orthotics is always contacted to the arm of the wearer, and support power is transmitted easily. By making the joint angle changes, passing the low pass filter which made T_{w1} the time constant as follows, the standard of a sensor value is continuously shifted.

$$\theta_{\mathrm{m}} = \frac{(f_{\mathrm{in}} - f_{\mathrm{min}})G_{\mathrm{A}}}{T_{\mathrm{w1}}s + 1} \tag{20}$$

In phase 2, the control phase becomes phase 3, which is the session of extension assist of the elbow when the robot is moved in the direction of extension. The velocity of the device uses velocity and acceleration of the wheelchair estimated during flexion. The wheelchair velocity v_{r}[m/s] during extension is (21). a_{w} is the estimated acceleration of the wheelchair and is added to v_{r} by time t_{w} from start time of extension assist. A_{w} is the gain with regards to acceleration. Eventually, it is assumed that the operator can change a value of A_{w} by the dial attached to the equipment. Because it is assumed that the wheelchair velocity won't slow down in Phase 2, the final value of the estimated wheelchair velocity $\hat{v}_{\mathrm{w}}$ is used as the initial velocity of the wheelchair in phase 3.

$$v_{\mathrm{r}} = \hat{v}_{\mathrm{w}} + A_{\mathrm{w}} a_{\mathrm{w}} t_{\mathrm{w}} \tag{21}$$

The velocity of the arm during assist $\dot{\theta}_{2\mathrm{a}}$ is obtained by the target wheelchair velocity v_{r}. The angular velocity of the elbow can be obtained by calculating as equation (22) from the viewpoint of inverse kinematics.

$$\begin{bmatrix} \dot{\theta}_{1\mathrm{a}} \\ \dot{\theta}_{2\mathrm{a}} \end{bmatrix} = J^{-1} \begin{bmatrix} v_{\mathrm{r}} \mathrm{C}\theta_{\mathrm{tan}} \\ v_{\mathrm{r}} \mathrm{S}\theta_{\mathrm{tan}} \end{bmatrix} \tag{22}$$

The obtained angular velocity is converted to the angle by integration calculation and is added to the target angle of phase 2 as (23). If the estimated wheelchair velocity causes an error because it is different from the actual wheelchair velocity, then the value of the pressure sensor functions to negate the gap by using not only the obtained target velocity but the state of the pressure sensor.

$$\theta_{\mathrm{m}} = (f_{\mathrm{in}} - f_{\mathrm{min}})G_{\mathrm{A}} + \frac{\dot{\theta}_{2\mathrm{a}}}{s} \tag{23}$$

Phase 3 is transitioned to phase 4 when the angle of the elbow becomes the constant angle, -50 [deg] in this research during phase 3. The robot has to shift to flexion for the next motion and has to convert the direction of after providing extension support. However, in wheelchair operation, after lengthening the elbow the velocity of elbow becomes the largest velocity. Therefore, if the robot stops immediately, large load is applied. The control phase is shifted to the flexion side gradually at a fixed velocity while the target angle passes the low pass filter with time constant T_{w2}. The velocity of the device is equation (24).

$$\dot{\theta}_{\mathrm{m}} = \frac{A_{\mathrm{fa}}}{T_{\mathrm{w2}}s + 1} \tag{24}$$

The velocity is slowed down until it reaches the decided flexion velocity A_{fa}. Support control is cancelled when the motion changes in the flexion direction and the value of the pressure sensor shows the input to an extension aspect, or when the velocity fully shifts in the flexion direction.

B. Verification Experiment by an Individual with C5-level CCI

This proposed method is mounted in the developed standalone type wearable robot and the verification experiment was conducted. The subject was a male in his 30s with C5-level CCI. A wheelchair operation was performed on a treadmill with the device attached. The wheelchair was supported by a cooperator in a fixed position until the measurement was started. The subject operated the wheelchair by himself with support from the device at the start of the measurement. The treadmill was set a speed in 1.0 [km/h] and an angle in 7.0% (about 4 [deg]). 4.0 [deg] was the angle of the limit that the operator can reach by himself when not using wearable robot. The wheelchair operation was tracked by motion capture and the wheelchair velocity was measured by color marking which was attached to the axle. The wheelchair operation is shown in Fig.4.

Fig. 4. Experimental setup of motion assistance for wheelchair operation with wearable robot by the individual with C5-level CCI (1.0[km/h], 7.0[%])

In this experiment, the physical constitution of the subject and the axle position of the wheelchair were measured by a motion capture system, and L_1=0.27[m], L_2=0.21[m], $(x_{\mathrm{w}}, y_{\mathrm{w}})$=(0.01,-0.61). The diameter of wheel of wheelchair is 0.61[m]. Each parameter in the control is T_{w1}=0.5, A_{w}, T_{w2}=0.1, A_{fa}=-50. The estimated wheelchair velocity using the assistance in the elbow extension period was set up to 0.3 [km/h] lower than the estimated result according to the operator. Since a motion of an arm differs from the operation which was being performed usually, it is considered to be adjustment for the operator not to be familiar with required motion perfectly. This experimental result is shown in Fig.5. Only the measurement result about operation of a right arm is shown so that a graph may become legible this time.

From the top sequentially, the input from the force sensor after passing low pass filter, the angle of the wearable robot (the elbow), the angular velocity of the wearable robot (the elbow), the wheelchair velocity, and the motion flag in the control system is shown. For the motion flag, 0 is at normal motion and flexion motion (phase 1), 1 is the preliminary period after flexion motion (phase 2), 2 is the extension period of the elbow and the support from the equipment (phase 3), and 3 is the end time of the extension support.

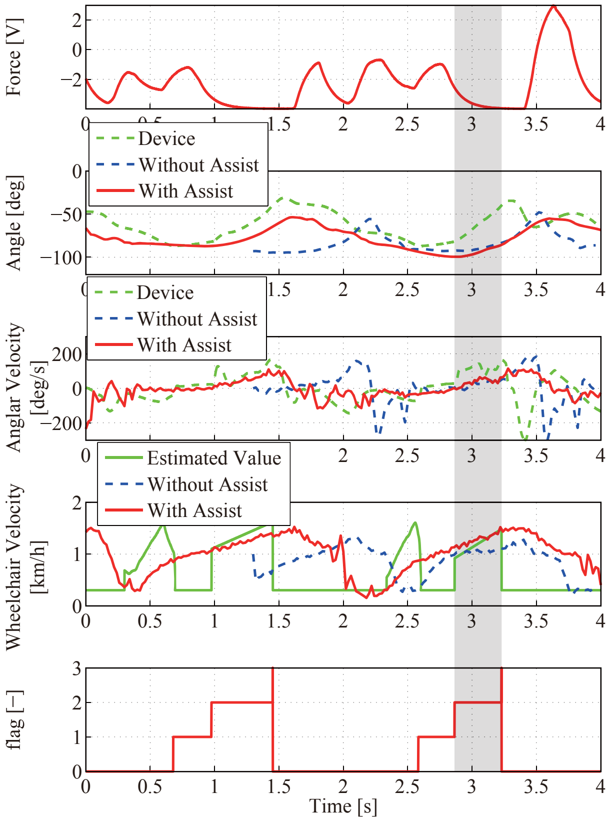

Fig. 5. Experimental results for assistance of wheelchair operation with wearable robot by the individual with C5-level CCI (1.0[km/h], 7.0[%])

Since the operator could accelerate only in the flexion motion when there is no support, the required acceleration could not be obtained. Therefore, because the operator could not perform the extension motion and must shift to the flexion motion immediately, the cycle of his motion was short. However, since the operator could accelerate the wheelchair even during extension of the elbow with support from the wearable robot, enough acceleration was provided. Therefore, the operator was able to have a leeway in operation and a cycle of motion became long about 1.5 times.

Thus, the result which appears notably was obtained as the effect by this proposed technology approaches an operator's limit.

VI. CONCLUSION

In this research, the estimate of parameters which could not be measured, such as the hand position and the shoulder angle from the position relationship of the body and the wheelchair during operation was performed. An estimate of the current wheelchair velocity from these calculated values using a wearable robot was developed in our laboratory. A control system which changes the force of the assistance depending on the obtained wheelchair velocity and supports the motion of the elbow only during extension of the elbow was developed. In addition, this control system was applied to a wearable robot and a verification experiment was conducted with the wheelchair in operation on a treadmill.

During operation of the wheelchair, the subject can perform the flexion motion by himself, and but can use assistant force depending on the motion movement at the time of flexion motion at the extension of the elbow. For the angle of slope which changes the load with regard to the operator, a good result was for the angle of slope which changes the load in relation to the operator because the system judges the assistant force needed, and can assist during the extension motion.

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