2011 IEEE International Conference on Robotics and Automation
Shanghai International Conference Center
May 9-13, 2011, Shanghai, China

Assistance Control of Wheelchair Operation Using Active Cast for the Upper Limb

Eiichi Ohara, Tatsuya Watanabe, Takeshi Oishi, Takaaki Aoki, Yutaka Nishimoto and Ken'ichi Yano

***Abstract*— Many people of all ages have sustained cervical cord injury in traffic accidents or sport accidents, and consequently suffered physical impairment. For individuals with paralysis of the lower limb who have also lost the ability to extend the elbow, many motions become difficult to perform in daily life, for example, independently operating a wheelchair or pushing open doors.**

In the future, wearable assist robots are expected to be incorporated into daily life. In order to be wearable, the assist robot must not limit the user's range of motion while being carried or used, and must be suitable for a wide range of situations. In this study, we developed an assist robot for upper limb movement which can assist wheelchair operation. To achieve this, we constructed a model of the upper limb during wheelchair operation with a manipulating force ellipsoid, and we developed an assistance control method for the upper limb using the device to apply force vectors. The effectiveness of the developed system is demonstrated experimentally.

I. INTRODUCTION

In 2009, the annual incidence of spinal cord injury (SCI) was reported to be approximately 12,000 new cases each year in the United States[1]. Furthermore, in Japan, the number of people with SCI or with cervical cord injury (CCI) is thought to be increasing year after year. Two out of three cases of SCI are caused by traffic accidents or falls.

Individuals with upper limb disorder have difficulty with mobility. For individuals with paralysis of the lower limb who have also lost the ability to extend the elbow many motions are difficult to perform in daily life, for example, independently operating a wheelchair or pushing open doors. An essential task for individuals with paraplegia is wheelchair operation. If individuals cannot apply sufficient force as a result of weakening or paralysis of the upper limb, they could face limitations such as tiring easily, and being unable to ascend a hill or travel over uneven terrain. One option for these individuals is to use a power-operated wheelchair[2], but this may limit their activities, because such wheelchairs are heavy and too large to fit inside most cars. In addition, the use of a power-assisted wheelchair may lead to a reduction of residual functions.

In recent years, research has progressed into wearable assist robots[3][4][5][6][7], which are versatile, have few restrictions on use, and are expected to be useful in daily life. In order to be wearable, the assist robot must not limit the user's range of motion while being carried or used, and must be suitable for a wide range of situations.

However, the target users are limited to able bodied and also disabled individuals who can apply the force with the upper limb. These systems amplify the force input by the user in the direction that it is applied. If the individual has limited ability to apply force, the system cannot compute a suitable assist force. Furthermore, providing too much assistance may lead to reduction of residual functions.

For instance, an individual uses the entire upper limb to operate a wheelchair using hand force. To assist this movement, an assistive force can be supplied if the user can exert force in all directions. However, if the user cannot perform the needed movement shown in Fig.1, they cannot exert force in the direction required to generate the assist force.

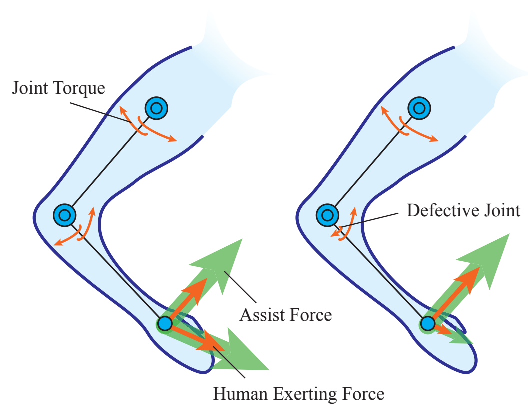

Fig. 1. Conceptual diagram of the assistive force and the force applied by users with (right) and without (left) muscular dysfunction

In this study, we developed a new type of a wearable motion assist robot (hereinafter called Active Cast) that imposes no limits on users and assists only movement in the case of dysfunction. This system does not simply amplify force. We constructed an upper limb model considering the available joint torque of the target user and computed an appropriate amount of assistance for wheelchair operation. This is not expected to result in a reduction of residual

This work was supported by Regional Innovation Cluster Program (City Area Type) : Southern Gifu Area.

Eiichi Ohara, Tatsuya Watanabe and Takeshi Oishi are with Graduate School of Engineering, Human and Information Systems Division, Gifu University, 1-1 Yanagido, Gifu City 501-1193, Gifu, Japan yanolab-watanabe@gifu-u.ac.jp

Takaaki Aoki is with Faculty of Medical Science, Dept. of Rehabilitation and Orthopedics, Gifu University Hospital, 3-25 kawabe, Gifu City 501-1198, Gifu, Japan ujimiya@gifu-u.ac.jp

Yutaka Nishimoto is with Faculty of Medical Science, Dept. of Surgical Nursing, Gifu Univ. School of Medicine, 1-1 Yanagido, Gifu City 501-1193, Gifu, Japan yutaka@gifu-u.ac.jp

Ken'ichi Yano is with Faculty of Engineering, Dept. of Mechanical Engineering, Mie University, 1577 Kurimamachiya-cho, Tsu City 514-8507, Mie, Japan yano-kn@gifu-u.ac.jp

978-1-61284-380-3/11/$26.00 ©2011 IEEE

functions. Then, we conducted an experiment on wheelchair operation using the developed Active Cast for the upper limb and showed the effectiveness of the proposed system.

II. MOTION CAPTURE ANALYSIS OF WHEELCHAIR OPERATION

We analyzed the characteristic of wheelchair operation by persons with disabilities of the upper limb by using motion capture. The participants were a male with SCI and a male with CCI. The participant with SCI had sustained injury to the lumbar spine. He is a wheelchair user, has full function of the upper limb, and is able to operate the wheel chair under his own force and travel freely. The other participant has C5-level CCI. He has paralyzed triceps brachii and is unable to apply force to the direction of elbow extension. Therefore, to operate a wheelchair he presses his hand against the rear of the rim and pulls upward. Figure 2 shows the measurement results for wheelchair operation by the participant with SCI.

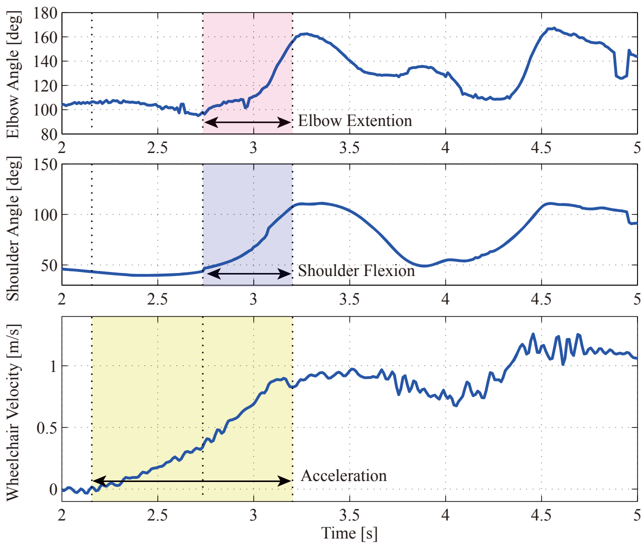

Fig. 2. Angles of upper limb and velocity of wheelchair during wheelchair operation by participant with lumbar cord injury

Figure 3,4 shows, from top to bottom, the elbow angle (positive value is the direction of extension), shoulder angle (positive value is the direction of flexion) and wheelchair velocity. To perform measurements, we placed colored markers on the participant's shoulder, elbow and wrist, and on the frame of the wheelchair. After recording the motion at 50 fps with a color camera, we analyzed the positions of color markers in three dimensions. In Fig. 2, for the participant with SCI, the elbow extension interval corresponds to the shoulder flexion interval (about 2.7 $\sim$ 3.2 s); it can also be seen that the wheelchair is accelerated during this interval. Calculating the velocity of the rim, we can see that the velocity can be approximated by a quadratic curve as shown in Fig. 3

The measurement results for wheelchair operation by the participant with C5-level CCI are shown in Fig. 4.

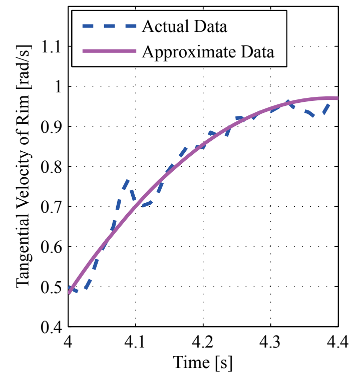

Fig. 3. Wheelchair velocity approximated by quadratic curve

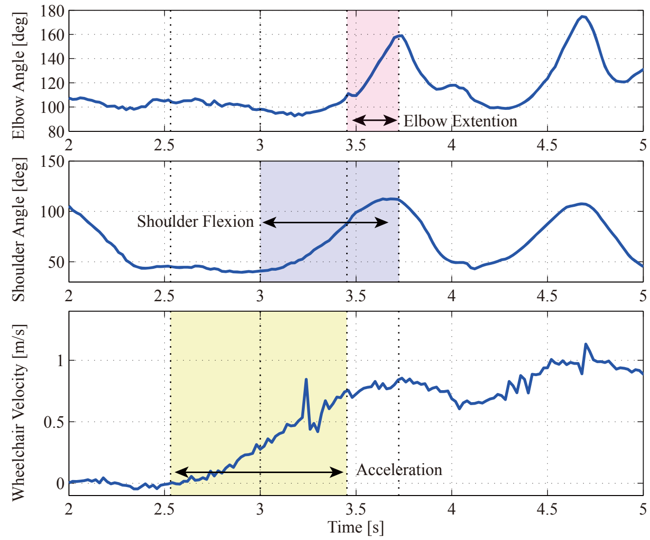

Fig. 4. Angles of upper limb and wheelchair velocity during wheelchair operation by individual with C5-level cervical cord injury

In the case of the participant with C5-level CCI, when the elbow is extended, the wheelchair is not accelerated. Elbow extension strength is needed in this interval for wheelchair operation, indicating that an individual with CCI cannot operate a wheelchair in the same manner as an individual with full function of the upper limb. For this participant with CCI, acceleration is observed only in the interval of 2.5 $\sim$ 3.4 s. During this interval, elbow flexion occurs, which is not impaired by the participant's paralysis. From this result, we can infer that the participant ordinarily applies force through flexion motion, not extension motion.

Therefore, in the case of individuals with C5-level CCI who have paralyzed triceps brachii but can extend the elbow, we expect that Active Cast can take advantage of residual function to assist in comfortable wheelchair operation.

III. ACTIVE CAST FOR THE UPPER LIMB

We developed the dual-arm robot with 1 degree of freedom, as shown in Fig. 5, to assist individuals who have disabilities of the upper limb. Active Cast does not prevent the user's residual function. It is designed to be lightweight and as simple as possible in order to ensure comfortable use. Moreover, Active Cast does not restrict movements not related to assistance, such as internal and external rotation in the forearm. This device is designed considering the human skeleton.

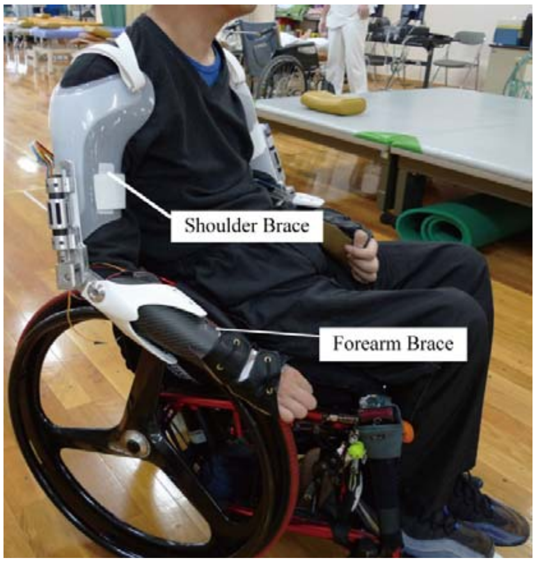

Fig. 5. Active Cast for the upper limb

The specifications of the device are shown in Table I.

TABLE I
SPECIFICATIONS OF ACTIVE CAST

Nominal torque	5.6[Nm]
Nominal speed	578[deg/s]
Weight	750[g]
Range of movement	135[deg]

We conducted an experiment to verify the performance of the developed Active Cast. The basic control technique for this device is admittance control based on signals from pressure sensors, as shown in Fig.6. The area enclosed the dashed rectangle and labeled P is a controlled object. The transfer functions $G_D(s)$ and $G_H(s)$ give the impedance of the device and the human arm; the impedance of the human body differs depending on the wearer. $G_S(s)$ is a characteristic of the pressure sensors. An input is reference velocity v_r. Outputs are the angle of rotation of the device (x_D), the angle of the elbow (x_e) and analog output value of the pressure sensor (f_c). The angle of the elbow during arbitrary operation is x_{ev}, the angle of the elbow resulting from the assist force is x_f, the difference between the angles of the device and the elbow is $\Delta x = x_e - x_D$, the sensor noise is n, the assist force is f_a and the reference force is f_r. The transfer function $G_A(s)$ is an admittance controller of a mass-damper system, and is shown in Eq. 1. The noise filter $G_F(s)$ is a low-pass filter with a 20 Hz cutoff.

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

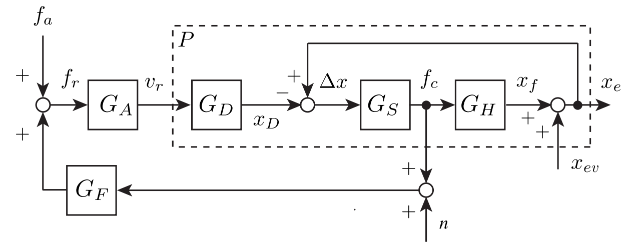

Fig. 6. Basic control block diagram of the motion assist robot for upper limb

Figure 7 shows the results of the verification experiment for Active Cast. As a result, the input of pressure sensors was found to correspond well to the device velocity. Therefore, the device can be operated properly by admittance control.

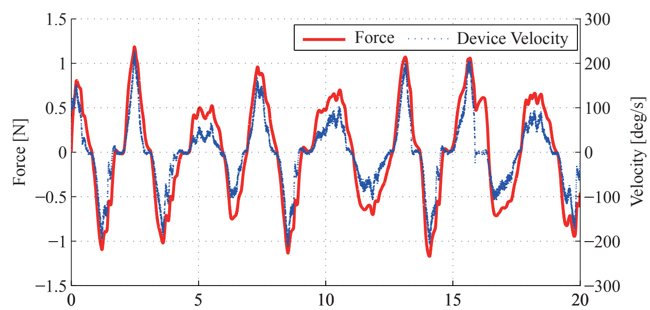

Fig. 7. Verification of operability of Active Cast for the upper limb

On the other hand, assist force f_a shown in Fig. 6 must be calculated for Active Cast to assist the user's motion. In this study, we set the assist force f_a based on the hand power that the user can exert and a reference value of hand power.

The control system for assistance is shown in the block diagram in Fig. 8. First, a reference velocity curve for the rim was calculated. Figure 3 shows that the velocity curve of the rim, which is approximated by a quadratic curve, as determined from the motion capture analysis. Accordingly, from the shoulder angle v_s and the elbow angle x_e for the motion of pulling the back part of the rim (self-operation), we then calculated a reference velocity curve v_a for the motion of pushing the front part of the rim (assisted operation). Next, we computed the reference hand power corresponding to the reference velocity curve v_a and the computed assist force f_a by comparison with the demonstrated hand power of the participant. In this case, we related the posture of the user's upper limb to the size of assist force f_a. And Active Cast exerts the assist forces f_a at each moment to the user.

IV. CALCULATING ASSIST FORCE USING MODEL OF THE UPPER LIMB

A. Model of Upper Limb During Wheelchair Operation

To use assist control as described previously, a model for hand power considering the available joint torque of

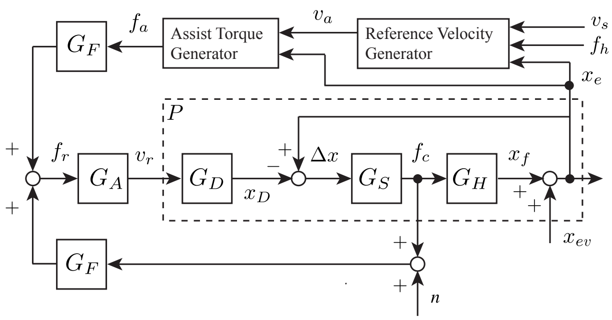

Fig. 8. Block diagram of assist control of Active Cast for the upper limb

the target user is needed. The reverse calculation must be considered to calculate the force vector for an arbitrary direction. Then, the redundancy of joints in a model of the human body can be problematic, and it is difficult to find a realistic value. In this study, we adopt the manipulating force ellipsoid[8]. It can provide the available hand power of the target user by forward calculation. We obtain the hand power vector by using the manipulating force ellipsoid and then calculate the assist force. Many individuals with dysfunction of the shoulder or elbow also have dysfunction of the hand. Individuals that are not able to grip instead press the carpal region (bottom hand) against the rim to operate a wheelchair. Therefore, we constructed a 5-degrees-of -freedom model of the upper limb from the shoulder to the elbow joint, excluding the forearm and hand (Fig. 9).

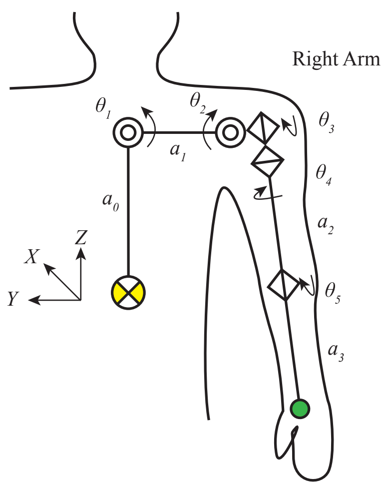

Fig. 9. Five-link model of upper limb

B. Description of Hand Power Using Manipulating Force Ellipsoid

Next, to calculate the assist force, we use a manipulating force ellipsoid to describe the demonstrated hand power of the participants. The manipulating force ellipsoid is used to evaluate the manipulating force of the hand quantitatively from the viewpoint of kinematics. $\boldsymbol{\tau} = J^T \boldsymbol{f}$ describes hand power in relation to joint torque, where $\boldsymbol{f}(m \times 1)$ is hand power, $\boldsymbol{\tau}(n \times 1)$ is the torque at each joint and J is a Jacobean matrix A set of hand power $\boldsymbol{f}$ using joint torque $\boldsymbol{\tau}$ with Euclidean norm $||\dot{\boldsymbol{\tau}}|| = (\dot{\tau}_1^2 + \dot{\tau}_2^2 + \dot{\tau}_n^2)^{1/2}$ that satisfies $||\dot{\boldsymbol{\tau}}|| \leq 1$ is shown as follows:

$$f^T (JJ^T)^{-1} f \leq 1 \tag{2}$$

This can be an m-dimensional ellipsoid. If the main radius of this ellipsoid is long, then large hand power is exerted in the radial direction.

However, this ellipsoid is based on the assumption that the maximum torque of each joint is constant and that there is no difference in positive and negative; thus, it is necessary to include differences in torque corresponding to posture and the direction of rotation. Then, we measured each joint torque of the participant and normalized $\hat{J} = JT_r(T_r = \mathrm{diag}[1/(\tau_{i\max} - \tau_{i\min})])$. Using $\hat{J}$, we described the manipulating force ellipsoid with the origin at the center of the available force of the target user, $\boldsymbol{f}_{mean}$, as follows:

$$(\boldsymbol{f} - \boldsymbol{f}_{mean})^T \hat{J}\hat{J}^T (\boldsymbol{f} - \boldsymbol{f}_{mean}) \leq 1 \tag{3}$$

Using this manipulating force ellipsoid, we can describe the measured hand power distribution by considering the participant's joint torque to calculate the hand power vector in an arbitrary direction.

Figure 10 shows the results of calculating manipulating force ellipsoids for an able-bodied person and an individual with C5-level CCI. As described previously, many individuals with dysfunction of the upper limb cannot grip the rim, and so a moment is not generated around the hand. Therefore, we use a cut plane of the ellipsoid considering only force components that are parallel to the sagittal plane to express the forces of wheelchair operation.

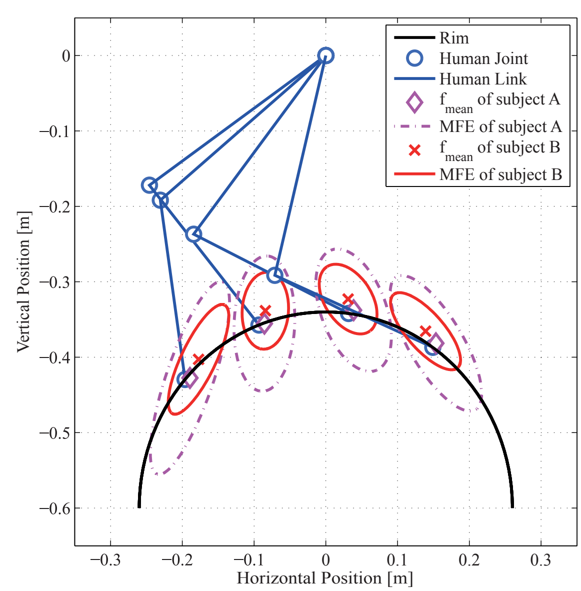

Fig. 10. Manipulating force ellipsoid (MFE): Participant A is able bodied, Participant B has C5-level cervical cord injury

In Fig. 10, the position of F_{mean} is far from the position of the hand, and the angle of the main radius of the ellipsoid is also different from the case of an able-bodied individual. In addition, the size of the ellipsoid of the individual with CCI is small. This signifies that individuals with CCI who cannot extend the elbow are not able to exert force to the direction of slightly inside the tangential direction of the rim required (at the front top-side of rim). These results correspond to the results of the motion capture analysis. We confirmed that we could express the direction and magnitude of hand power that the participant can demonstrate by using the manipulating force ellipsoid.

C. Calculating Assist Force Using Manipulating Force Ellipsoid

We calculate the assist force using the manipulating force ellipsoid. To obtain the assist force, we compute the intersection of the manipulating force ellipsoid and the reference hand power vector.

The relation between manipulating force ellipsoid and reference hand power vector is shown in Fig. 11. We set $[x_{Fmean},\ y_{Fmean}]$ as the center of the ellipsoid, where $\boldsymbol{u_1}/\sigma_1 = m_{al}$ and $\boldsymbol{u_2}/\sigma_2 = m_{as}$ are the major and minor axis of the ellipsoid, α is the slope of the ellipsoid, R_α is the rotation matrix describing the slope of the ellipsoid, $[x_s,\ y_s]$ is the origin of the reference hand power vector (i.e., the position of the hand), $[x_t,\ y_t]$ is the end of the reference hand power vector and $[x_v,\ y_v]$ is the intersection of manipulating force ellipsoid and reference hand power vector.

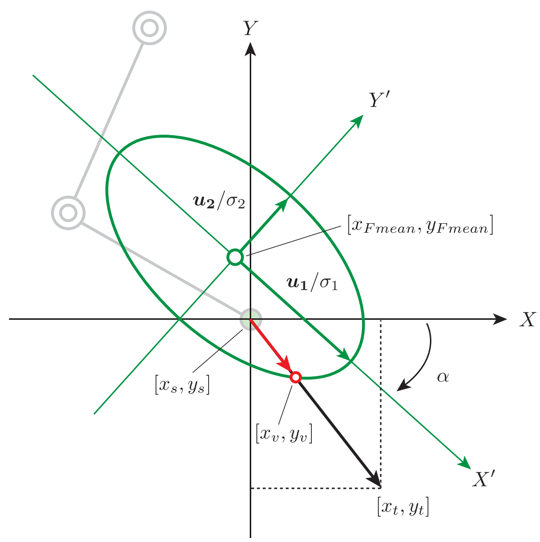

Fig. 11. Intersection of the manipulating force ellipsoid and vector of reference hand power

The main axis of the manipulating force ellipsoid can be obtained to perform singular value decomposition $\hat{J} = U\Sigma V^*$, where the first vector of U is $\boldsymbol{u}_i$,σ and the diagonal element of σ of row i column i is σ_i. First, the origin $[x_s,\ y_s]$ and the end $[x_t,\ y_t]$ of reference generative force vector are projected along the axis of the ellipsoid X', Y'.

$$\begin{bmatrix} x_{siR} \\ y_{siR} \end{bmatrix} = R_\alpha^{-1} \begin{bmatrix} x_s \\ y_s \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} x_{tiR} \\ y_{tiR} \end{bmatrix} = R_\alpha^{-1} \begin{bmatrix} x_t \\ y_t \end{bmatrix} \tag{5}$$

Next, we calculate the slope and the intercept when the primary expression of the vector is given in X', Y' coordinates:

$$k = \frac{y_{tiR} - y_{siR}}{x_{tiR} - x_{siR}} \tag{6}$$

$$l = y_{siR} - m x_{siR} \tag{7}$$

We calculate the intersection of the ellipsoid and the primary expression of the vector in the X', Y' coordinates,

$$\begin{bmatrix} x_{viR} \\ y_{viR} \end{bmatrix} = \begin{bmatrix} \frac{q+\sqrt{q^2-pr}}{p} \\ \frac{k(q+\sqrt{q^2-pr})}{p} + l \end{bmatrix} \tag{8}$$

Then,

$$p = \frac{1}{m_{al}^2} + \frac{k^2}{m_{as}^2} \tag{9}$$

$$q = \frac{-kl}{m_{as}^2} \tag{10}$$

$$r = \frac{l^2}{m_{as}^2} - 1 \tag{11}$$

This equation can be converted back into X, Y coordinates as follows:

$$\begin{bmatrix} x_v \\ y_v \end{bmatrix} = R_\alpha \begin{bmatrix} \frac{q+\sqrt{q^2-pr}}{p} \\ \frac{k(q+\sqrt{q^2-pr})}{p} + l \end{bmatrix} - \begin{bmatrix} x_s \\ y_s \end{bmatrix} \tag{12}$$

From this, we can obtain the intersection of the ellipsoid and the arbitrary vector. It is converted to assist torque by Active Cast, where $[x_v,\ y_v]^T$ is the assist force vector.

V. VERIFYCATION EXPERIMENTAL BY ACTIVE CAST

We conducted an experiment to verify the method presented in this paper by implementing to Active Cast. The experiment was conducted by adding a suitable load to the tire of a wheelchair that was set on a stand. The subject was an able-bodied male in his 20s. Then, the rotational velocity of the rim and corresponding tangential operational force were calculated in a preliminary experiment, and we determined the reference curve v_a. The experiment was recording by using motion capture and myoelectric sensors placed on the triceps brachii for the evaluation of the elbow extension force. The calculated assist torque was converted to the force at the position of the pressure sensor on Active Cast and added to the input from the sensors.

Figures 12 and 13 show the results of the experiment with and without motion assistance. Respectively from top to bottom, the angle of Active Cast, the assist force, the values from pressure sensors and the velocity of the rim are shown.

From the elbow angle and the assist force, the assist force can be seen to be added only during elbow extension.

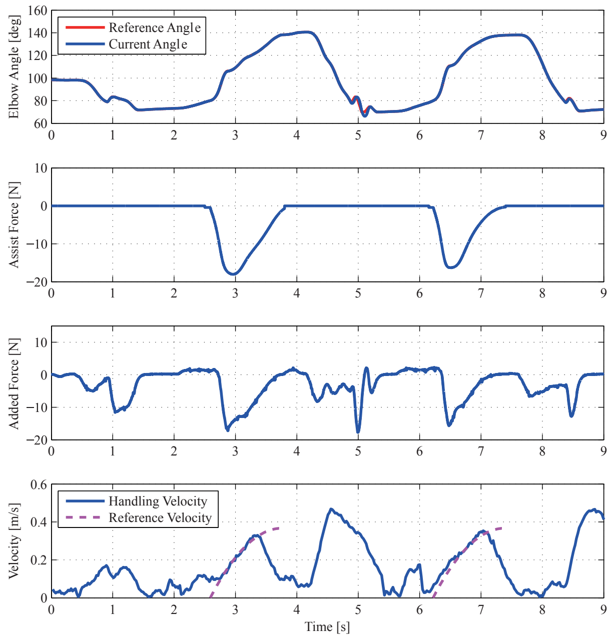

Fig. 12. Experimental results of wheelchair operation with motion assist

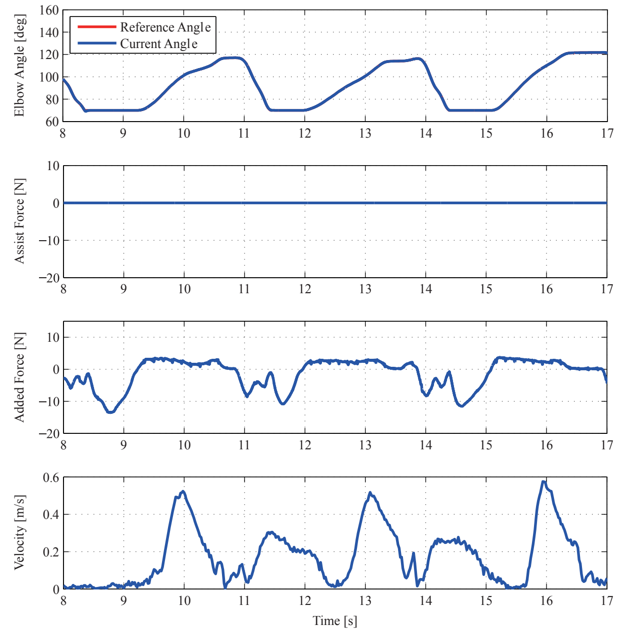

Fig. 13. Experimental results of wheelchair operation without motion assist

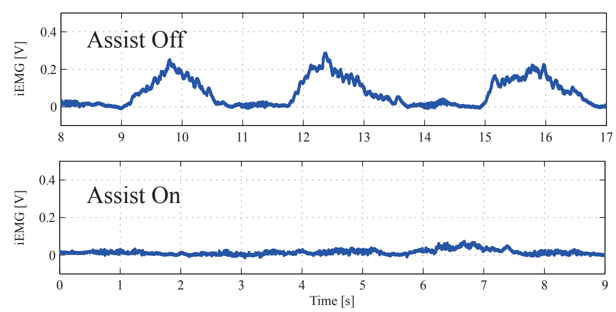

Fig. 14. Comparison of iEMGs with and without motion assist

Furthermore, because the assist force decreased as the elbow was extended, we can infer that an assist force equal to the target value was applied to the upper limb. Looking at the interval when assist force was added, the reference velocity can be seen because of the rim was accelerated sufficiently and the acceleration curve corresponded to the quadratic curve.

From the results of integrated electromyography (iEMG) for the triceps brachii during elbow extension, it was found that the participant did not exert force during elbow extension because iEMG measured with motion assist was less than that without motion assist. These results shows that this proposed method is effective because the reference velocity could be reached, even though the participant did not exert force during elbow extension.

VI. CONCLUSION

In this study, we constructed a model of upper limb motion for assisted wheelchair operation. Then, we proposed a method for setting the assist force using the manipulating force ellipsoid for individuals with dysfunction of the upper limb. Finally, by implementing Active Cast using the proposed method, we were able to assist wheelchair operation such that it was approximately the same as operation by an able-bodied person, even though the participant could not apply force to the required direction.

REFERENCES

[1] the National Spinal Cord Injury Statistical Center. (2009) Facts and figures at a glance. FactsApr09.pdf. [Online]. Available: https://www.nscisc.uab.edu/

[2] C. Urdiales, M. Fernandez-Carmona, J. Peula, R. Annicchiaricco, F. Sandoval, and C. Caltagirone, "Efficiency based modulation for wheelchair driving collaborative control," in *Proc. IEEE Int. Conf. on Robotics and Automation*, Anchorage, Alaska, USA, May 2010, pp. 199–204.

[3] K. Yano, J. Hashimura, T. Aoki, and Y. Nishimoto, "Flexion-extension motion assistance using an upper limb motion-assist robot based on trajectory estimation of reaching movement," in *Proc. IEEE EMBS Annual Int. Conf.*, Minneapolis, Minnesota, USA, Sept. 2009, pp. 4599–4602.

[4] H. Kawamoto and Y. Sankai, "Power assist method based on phase sequence and muscle force condition for hal," *Advanced Robotics*, vol. 19, no. 7, pp. 717–734, 2005.

[5] K. Kiguchi, M. Rahman, M. Sasaki, and K. Teramoto, "Development of a 3dof mobile exoskeleton robot for human upper-limb motion assist," *Robot. Auton. Syst.*, vol. 56, no. 8, pp. 678–691, 2008.

[6] H. Kobayashi, H. Nozaki, and T. Tsuji, "Development of power assist system for caregiver by muscle suit," in *Proc. IEEE Int. Conf. on Mechatronics and Automation*, Harbin, China, Aug. 2007, pp. 180–185.

[7] Y. Mao and S. K. Agrawal, "Wearable cable-driven upper arm exoskeleton - motion with transmitted joint force and moment minimization," in *Proc. IEEE Int. Conf. on Robotics and Automation*, Anchorage, Alaska, USA, May 2010, pp. 4334–4339.

[8] R. Koeppe and T. Yoshikawa, "Dynamic manipulability analysis of compliant motion," in *Proc. IEEE Int. Conf. on Intelligent Robots and Systems*, Grenoble , France, Sept. 1997, pp. 1472–1478.