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Flexion-Extension Motion Assistance Using an Upper Limb Motion-Assist Robot Based on Trajectory Estimation of Reaching Movement

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Abstract— **People of all ages have suffered impairment in traffic accidents or sport accidents, and these individuals worry about dysfunction of their upper limbs, but they can recover from dysfunction by rehabilitation. In this study, we developed an assistive robot for upper limb movement that has high rehabilitation effectiveness. To achieve this, we proposed a reaching movement support method that considers an expanding joint's range of motion. The effectiveness of our method is shown through experiments.**

I. Introduction

About 13% of physically handicapped persons in Japan have dysfunction of the upper limb. Examples of dysfunction of the upper limb are aftereffects caused by external injury and brain paralysis resulting in a decline in physical ability. The main symptoms of this type of injury are limited joint range of motion and slow motion. People of all ages have suffered impairment in traffic accidents or sport accidents, and these individuals worry about dysfunction of their upper limbs, but they can recover from dysfunction by rehabilitation. Robots support those who have dysfunction of the upper limb, and this leads to rehabilitation, improved quality of life (QOL) of impaired persons, and a lightened load for medical and welfare workers.

Rehabilitation of the muscles and improved joint range of motion are effective in improving patient QOL, but only in the case of intentional motion. Many rehabilitation robots have been developed, but they are used only for rehabilitation in the hospital, performing tasks such as moving arms periodically. These robots cannot be used for assisting patients in their daily life.

In this study, we developed an assistive robot for upper limb movement that has high rehabilitation effectiveness. By using the robot in daily life, patients can recover from dysfunction. This robot supports flexion and extension of the elbow by providing reaching movement support that considers an expanding joint's range of motion. Our reaching movement support method is based on trajectory estimation of the reaching movement.

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II. Assistive robot for the upper limb movement

The assistive robot for the upper limb movement developed in this study is shown in Figure 1. This robot is a manipulator with 4 degrees of freedom, and supports the flexion and extension motion of the elbow, which is the motion that requires the most power of the movements of the upper limb joints, so the drive axis is only in the 1st joint of the robot. The 2nd joint is a free joint for the medial rotation and external rotation motion of the elbow, the 3rd joint is a free joint used for absorbing the elastic skin in the joint motion, and the 4th joint is a free joint used for the pronation and the supination motion of the wrist. These free joints contribute to the free joint motions of the upper limb. The maximum torque and speed of this robot are 7[Nm] and 226[deg/s], respecitvely. The super-thin film pressure sensor "FlexiForce" made by the NITTA Corporation senses the human force. Eight FlexiForce sensors are installed in the robot, and these sensors measure the force of flexion and extension motion and the medial rotation and external rotation motion of the elbow, which comprises the fixed pressure between the robot and the human arm. This robot is fixed on the upper limb with a shoulder supporter.

Fig. 1. Novel assistive robot for the upper limb movement

III. Motion assist with variable dumping method

A. Variable dumping control

In this study, position-based variable dumping control is applied to the robot. The viscosity changes depending on the control force[1]. The variable damping based on the operator's force has a unique feature caused by the bell-shaped velocity. The bell-shaped velocity is well known as an ideal trajectory of a reaching movement of human arms[2][3][4]. The control law is expressed as Eq.(1) and Eq.(2).

$$k_{amp}\tau_h = M_I\ddot{\theta}_d + D_I\dot{\theta}_d \quad (1)$$

$$D_I = D_s \cdot \frac{A}{|\tau_h| + A} \quad (2)$$

where, M_I, D_I are the inertia and viscosity in the mechanical impedance, respectively, D_s, A are the initial viscosity and the reduction rate of viscosity in the variable damping, respectively, and τ_h, k_{amp} are the control force by human and the amplifier rate of force, respectively.

The result of the variable dumping control is shown in Figure 2. Input τ_h is the positive value of the sinusoidal wave (amplitude 1.0[Nm], frequency π[rad/s]), and other parameters are $M_I = 1.0 \times 10^{-3}$[Nm/(deg/s^2)], $\tau_k = 0$[Nm], $A = 0.5$[-], $D_s = 0.2$[Nm/(deg/s)]. This control method represents the natural trajectory of the joint motion, because the velocity waveform is bell-shaped.

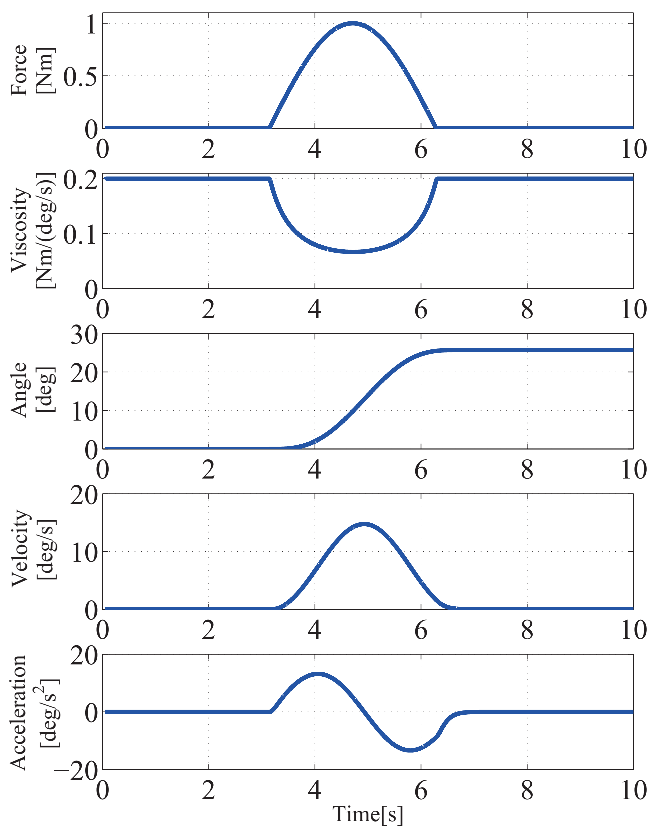

Fig. 2. Experimental result of the variable damping based on operator's force

B. Estimation of the motion trajectory

The variable damping control explained in the foregoing section cannot help people with limited range of joint motion, as this method is the same as the conventional power-assist method. In the case of support for people with dysfunction of the upper limb, the amplifier rate of force must be very large. Although it is possible that this method could assist these people, it cannot be denied that the system becomes very cranky and dangerous.

To solve this problem, we have adopted predictive control, which estimates the reaching position in cases where the user cannot move by his own force, based on the motion in the range of the user's intended motion. Namely, the control system estimates the future movement during the estimating interval shown in Fig.3. The reaching motion consists of acceleration and deceleration intervals. There are three estimated motions, as shown in Fig.4.

- Case 1: In accelerating, decelerate after the additional acceleration
- Case 2: In decelerating, continue to decelerate
- Case 3: In constant velocity, maintain velocity

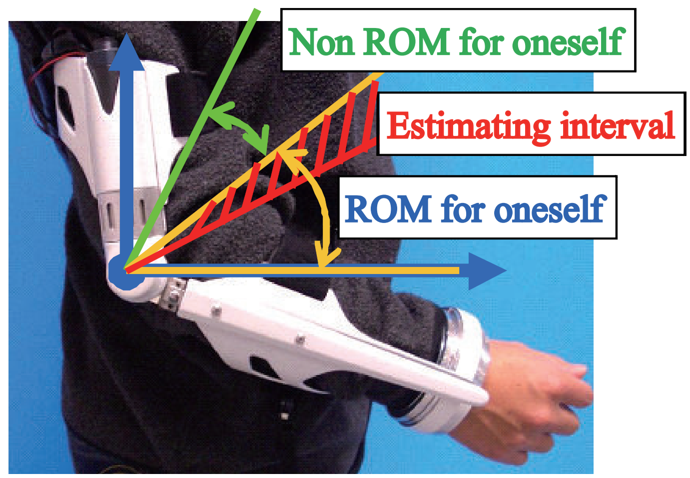

Fig. 3. Definition of joint range of motion

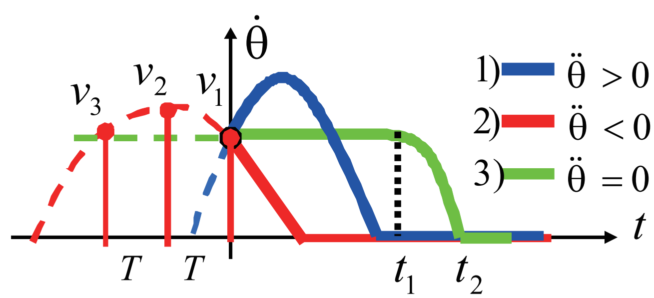

Fig. 4. Estimated trajectory of the reaching movement

If the estimated motion is Case 1 or Case 2 , the estimated trajectory of velocity can be approximated to the quadratic function. The estimated trajectory is defined as Eq.6 based on the velocity date sampled with sampling interval T in the estimating interval.

$$\dot{\theta}_{est} = -at^2 + bt + c \quad (3)$$

$$a = \frac{v_3 - 2v_2 - v_1}{2T^2} \quad (4)$$

$$b = \frac{v_3 - 4v_2 + v_1}{2T} \quad (5)$$

$$c = v_1 \quad (6)$$

By contrast, if the estimated motion is Case 3, it can be estimated that maintaining the velocity is desired, but the timing of the deceleration cannot then be estimated. In this case, the estimated trajectory is defined as Eq.7 and Eq.8, identifying this motion as the deceleration motion after maintaining the velocity for a certain period of time. v_1 is the velocity when switching to the automatic control, t_1 is the duration of the uniform motion, and t_2 is the termination time of the motion; t_1 and t_2 are determined through a trial-and-error process.

$$if \quad t < t_1 \quad \dot{\theta}_{est} = v_1 \quad (7)$$

$$if \quad t \geq t_1 \quad \dot{\theta}_{est} = -\frac{v_1}{t^2}(t - t_1)^2 + v_1 \quad (8)$$

C. Input shaping of the estimeted trajectory

The estimated trajectory is approximated not to match the bell-shaped velocity but to match the quadratic function velocity. As a result, this estimated motion will be an uncomfortable motion used as the target trajectory of the robot. Therefore, this quadratic estimated trajectory must be made to conform to the bell shape by the low-pass filter to improve the operability, as shown in Fig.5.

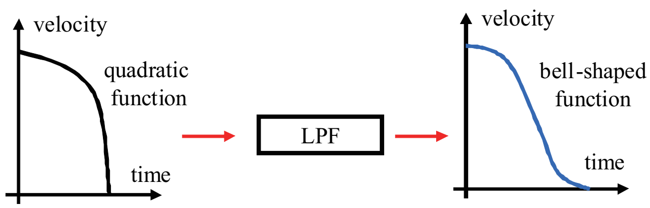

Fig. 5. Bell shape forming of quadratic function by LPF

The control switches into the automatic mode when the motion crosses the switching angle, and into the manual mode when the velocity becomes zero. There is no discontinuity in switching into the automatic mode, but there is a discontinuity in switching into the manual mode, as the robot lifts the upper limb because the user doesn't have the muscle force to accomplish this movement. It is very dangerous to switch into the manual mode from the auto mode with the sensor sensing the high force. The set-off with the first-order lag element avoids this phenomenon, as shown in Fig.6.

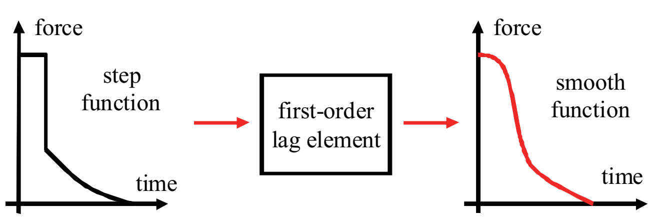

Fig. 6. Smoothing discontinuous trajectory by 1st order lag element

The robot follows the trajectory obtained from the variable damping control and the estimated reaching trajectory control by the PID control. The total control system is shown in Fig.7. The PID parameters are the proportional gain $K_P = 0.5$, the integral gain $K_I = 0.1$, and the differential gain $K_D = 0.01$.

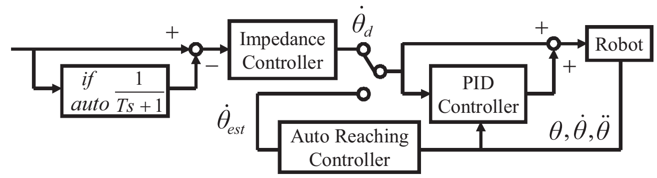

Fig. 7. Motion-assist control based on trajectory estimation of reaching movement

IV. EXPERIMENTAL RESULTS

A. Verification of the proposed method

The behavior of this system in switching the modes is shown in Fig.8. In this experiment, the user flexes and extends his elbow only once. In Figure 8, the 1st graph is the input to the variable damping control, the 2nd graph is the force by the human, the 3rd graph is the determination of the control mode, the 4th graph is the angle, the 5th graph is the velocity, and the 6th graph is the estimated velocity.

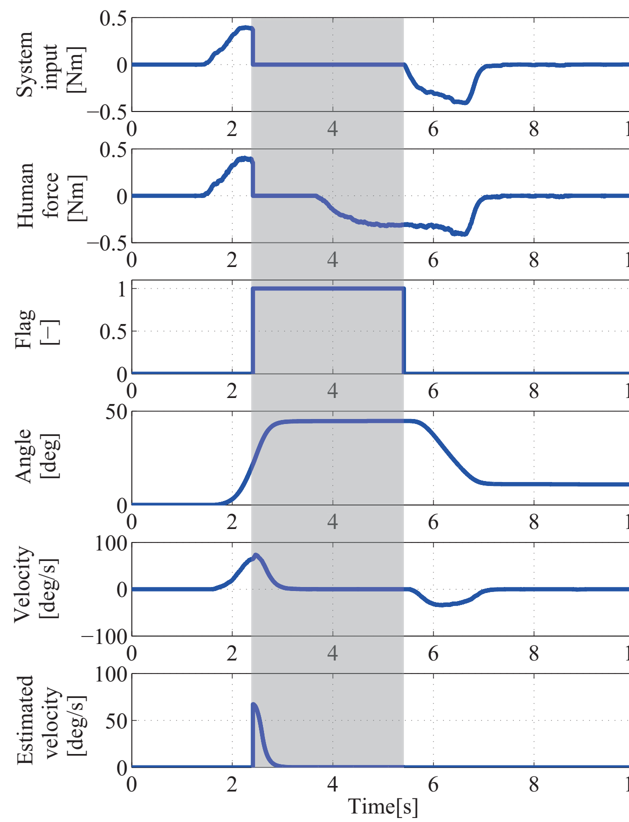

Fig. 8. Experimental result of mode switching

The area blacked out is controlled in the automatic mode. The parameters of the variable damping are $M = 0.0002$[Nm/(deg/s^2)], $D_0 = 0.5$[Nm/(deg/s)], $A = 0.5$[-], $\tau_{ks} = 0.05$[Nm], and $\tau_{ksi} = 0.01$[Nm], and the switching angle is 30[deg]. The automatic mode continues for 3 seconds. The system remains static no matter whether the user applies force into the extension in the automatic mode. The control force doesn't exponentially increase in switching into the manual mode even if the user applies force.

The result of the estimating accuracy is shown in Figure 9. In this experiment, the user flexes his elbow in the target angle 5 times. The target angle is 40, 60, 80, 60, and 80[deg]. The parameters are the same as those in the previous experiment.

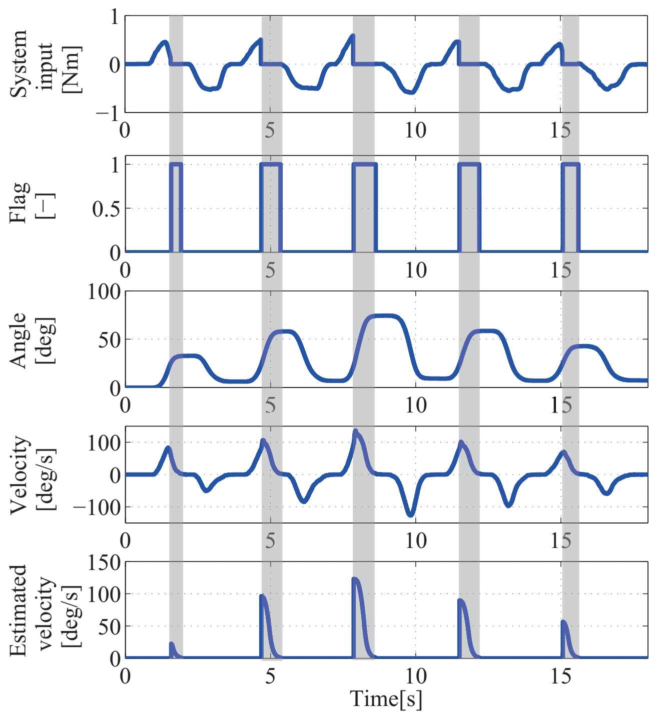

Fig. 9. Experimental result of reaching angle estimation

There exists the ± 5[deg] error, but this experiment produces an excellent result because this control doesn't demand positioning accuracy. The velocity form is bell-shaped, and the system is controlled continuously and smoothly even if the reaching position is distant.

B. User test

This system is tested by a patient with a brachial plexus injury. In this type of injury, the brachial plexus is damaged by excessive impact as typified by what occurs in a motorcycle accident. The examinee can flex his elbow at 40[deg] and cannot flex over 40 [deg] with his muscle force.

This examinee is assisted by only the variable damping control and the variable damping control with the reaching motion-assist method. The result is shown in Fig.10. The maximum extending angle of the examinee is set to 0[deg], the range of joint motion achievable by the subject's own power is $0 \sim 30$[deg], the estimating range is $25 \sim 30$[deg], and the range of joint motion not achievable by the subject's own power is $30 \sim 80$[deg]. In only the variable damping, the examinee cannot flex his elbow above 40[deg] even if he flexes his elbow fast and furiously. But, in the variable damping with the reaching motion-assist method, he can flex his elbow first to 60[deg] in the first motion and then to 70[deg] in the second motion. As this result shows, this system can estimate the arbitrary reaching angle, so this method is efficacious.

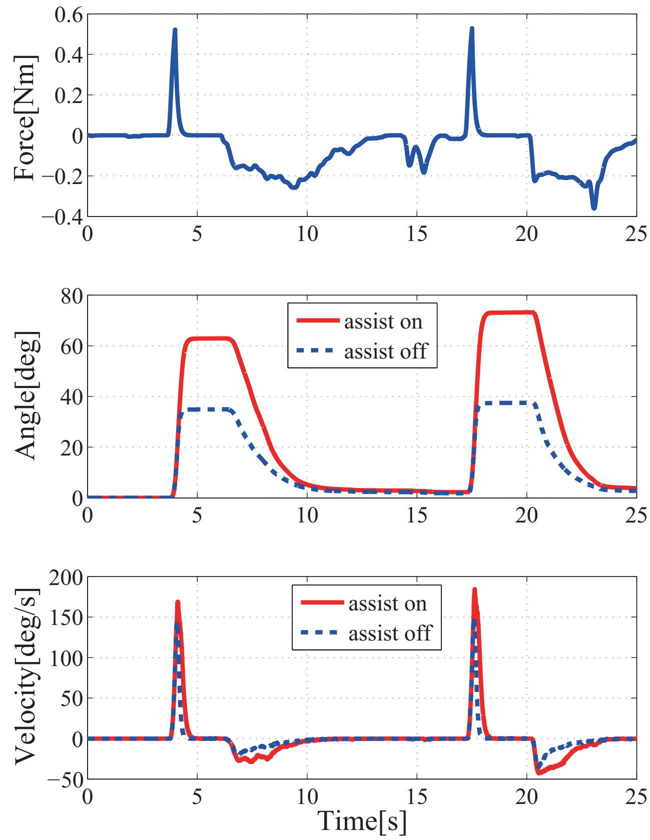

Fig. 10. Experimental results

V. Conclusion

In this study, we proposed a motion-assist method based on the trajectory estimation of the reaching motion, and the effectiveness of this method was revealed in a clinical experiment by a patient with a brachial plexus injury. This system provides reaching motion assistance to people who cannot achieve a desired range of joint motion by themselves.

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