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Control of Wearable Motion Assist Robot for Upper Limb Based on the Equilibrium Position Estimation

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Abstract— **In this paper, we propose a robotic system for assisting patients who have upper limb dysfunction in performing reaching movements through flexion. Since upper limb motion is more strongly needed than lower limb mobility for near work, a patient's level of recovery of upper limb function influences daily life. Recently, with the widespread application of robotic technology in rehabilitation medicine, active movement has often been noted to be more important than passive movement for rapid recovery. A novel control method for assisting upper limb movement by using a control system with two degrees of freedom is proposed. In the process of estimating the trajectory, the minimum jerk criterion is used to compute the velocity trajectory and to determine the reach position. The aim is to eventually develop a movement assistance system for the upper limb which will enable wearers to perform flexion and extension covering ranges of motion which are otherwise impossible to achieve autonomously. The effectiveness of the developed system is demonstrated experimentally.**

I. INTRODUCTION

At present about 13% of all people with disabilities in Japan have been reported to have upper limb dysfunction. The effects of injury, cerebral paralysis and disability due to aging have been pointed out as leading causes of upper limb dysfunction. A main problem in upper limb dysfunction is the inability to perform smooth movement of joints, in which the range of motion is limited and the muscle strength is lowered. Although there are cases where these conditions can be improved by surgery or rehabilitation, there is a limit to the extent of recovery, and there are a large number of individuals who experience difficulties in daily life. In particular, for individuals with upper limb dysfunction caused by damage to the nervous system who undergo surgery and rehabilitation in order to restore the functionality of the affected limb, complete recovery is difficult.

In recent years, movement assistance by means of wearable robots has been attempted for individuals with upper limb dysfunction[1]-[3]. However, conventional robots often can only repeat predefined movements, and therefore their application in daily life is impractical. In addition, the concept of variable viscoelasticity has not been taken into account to date, and numerous studies have investigated robot-assisted movements by using only sensory information as feedback. Hence, there are difficulties in implementing agile, smooth and delay-free upper limb movements similar to natural human movements.

Therefore, with the aim to implement agile and smooth human-like assisted movements, we propose a novel method for assisting upper limb movement by using two degrees of freedom control system. In this model, the movements of the flexor and the extensor are modeled and a trajectory is estimated, after which the obtained information is used as feedback to adjust the viscoelasticity of the muscles. The aim is to eventually develop a movement assistance system for the upper limb which will enable wearers to perform flexion and extension covering ranges of motion which are otherwise impossible to achieve autonomously.

II. WEARABLE MOTION ASSIST ROBOT FOR UPPER LIMB

Fig. 1 shows the wearable motion assist robot for the upper limb which is used in this research. The only moving part is at the primary joint; this part provides assistance with only flexion and extension of the elbow. This part is moved by DC motor and exerts the torque reduced by Gearhead, worm gears. Pronation and supination are fixed, while the shoulder joint and the elbow can perform free revolution and involution; the construction is capable of providing assistance only with flexion and extension of the elbow without interfering with residual functionality. The total weight is 1.0[kg], and the moving part incorporates a brushless DC motor manufactured by Maxon Motor. Its maximum speed is 578[deg/s], and the maximum torque exerted on the forearm is 4.1[Nm]. The range of movement is 135 [deg]. A film pressure sensor with a thickness of 0.127[mm] is used for movement sensing.

A. Position-based variable impedance control

In this study, we focus on individuals who are capable of autonomous movements within a certain range and no autonomous movements beyond that range. Such conditions can be seen in individuals with neuronal injury from an accident and whose recovery through surgery and rehabilitation is limited. Here, the range in which autonomous movements are possible is referred to as autonomous movement range, and the range where no such movements are possible is referred to as assisted movement range.

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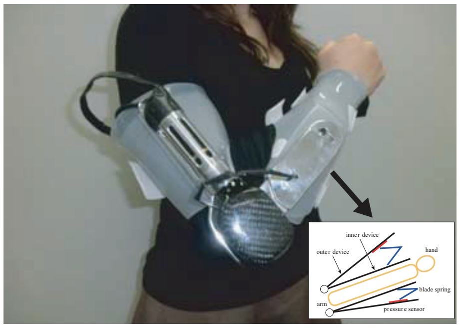

Fig. 1. Movement assistance robot for the upper limb

In providing assistance to individuals with upper limb dysfunction, it is desirable to retain the ability to move within the autonomous movement range to the greatest extent possible since using the affected limb helps to prevent worsening of the condition and also aids rehabilitation. For this reason, the upper limb is not forcefully moved within the autonomous movement range in order to allow the wearer to perform natural movements on their own accord. Thus, movement assistance is provided through position-based impedance control within the autonomous movement range. A model of the control law is shown in Fig. 2. Impedance parameter is varied based on iEMG, which enables delayfree movements, in accordance with a biological signal, to be performed by lowering the viscosity coefficient faster than the movement is realized.

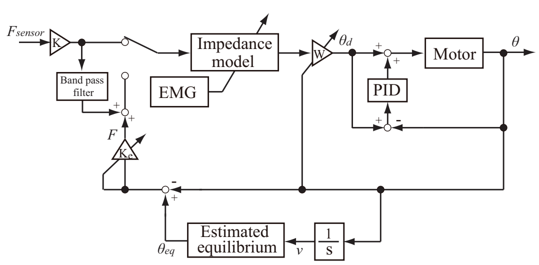

Fig. 2. Schematic block diagram of the controller

B. Musculoskeletal model of the upper limb

A musculoskeletal model of the upper limb is considered in order to model movements performed by humans in everyday life. In the human musculoskeletal system, each joint is accompanied by at least two muscles that cause the motion at that joint. In addition, there are cases where a single muscle drives motions at two joints. For this reason, the human musculoskeletal system is extremely complex and rather difficult to model. In recent years, advances have been made in this field, with the result that a number of models of the human musculoskeletal system have been proposed, as presented in Fig. 3[4].

In the present model, we obtain the following equation of motion for flexion of the elbow, which takes the muscles into account:

$$M_h\ddot{q} + g_h(q) = d\{(u_f - u_e) - (u_f + u_e)(kq - b\dot{q})\} \quad (1)$$

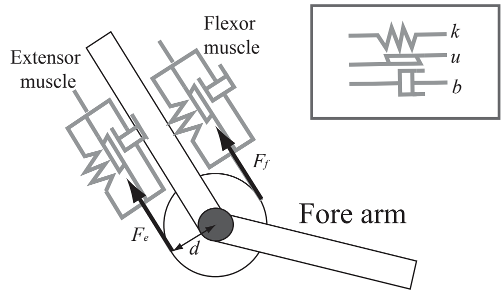

Fig. 3. Musculoskeletal model of the upper limb

Here, M_h is denoting the moment of inertia of the forearm, g_h is the gravitational acceleration term, q is the rotation angle, k is the elasticity, b is the viscosity, d is the radius of a lever arm, u_f and u_e are the contraction force of flexion and extension, respectively.

In general, the equation of motion for a manipulator with multiple joints can be written in the following form:

$$M_r\ddot{q} + C_r\dot{q} + g_r(q) = \tau_r \quad (2)$$

Here, M_r, C_r and g_r are the inertia, viscosity and gravitational acceleration coefficients of the robot, respectively, and τ_r is the torque generated by the robot. If the robot and the wearer are considered to move together as a unit, the model of the entire system can be regarded as a superposition of (2) and can therefore be defined by the following equation:

$$(M_r + M_h)\ddot{q} + C_r\dot{q} + g_r(q) + g_h(q) = \tau_r + \tau_h \quad (3)$$

In order to improve safety, the velocity inhibition coefficient is added to the reference velocity waveform so that an unreasonable motion may not be carried out near the limit range of motion (ROM).

If $\dot{\theta} > 0$ and $\frac{(ROM)}{2} < \theta \leq (ROM)$ or if $\dot{\theta} < 0$ and $0 \leq \theta < \frac{(ROM)}{2}$, the weight coefficient W is following:

$$W = -\frac{4}{(ROM)^2}\theta^2 + \frac{4}{(ROM)}\theta \quad (4)$$

III. Estimating the Equilibrium Position for Virtual Springs

Similarly to the way humans usually use a feed-forward process to determine the position to which they wish to move, natural flexion and extension can be implemented, even in the assisted movement range, by estimating the reach position before entering the assisted movement range, assigning it as feed-forward and adjusting the viscosity in the vicinity of the target value.

A. Estimating the reach position based on the minimum jerk criterion

First, we explain the method of estimating the reach position through a feed-forward process. A reaching movement, which is performed when a human extends the upper limb toward a target, is a fundamental movement performed in daily life without conscious thought, and therefore it might appear to be extremely simple at first glance. However, reaching movements are realized through contributions from various parts of the brain, and even now almost nothing is known about the processes occurring in the brain during the execution of reaching movements. Nonetheless, the brain certainly estimates the trajectory when performing reaching movements since the trajectories of the forearm for a wide range of reaching movements are uniform, with distinctive characteristics. More specifically, the trajectory of the forearm in an external coordinate system is virtually a straight line, the velocity of the fingers in an external coordinate system traces a roughly symmetric bell curve with respect to time, and the acceleration at the starting point and the end point is zero. Even though there are countless trajectories from the starting point and the end point, the brain prepares trajectories obeying certain uniform characteristics.

A representative evaluation function in this case is the square integral of the jerk (the time derivative of acceleration, in other words, the third time derivative of position). Hogan and Flash showed that the trajectory of a reaching movement is the trajectory that minimizes the following evaluation function, as well as that the velocity waveform is a bell curve [5]. The estimated velocity trajectory can be calculated from the finger position equation that minimizes the evaluation function for the minimum jerk criterion.

By using the velocity data (v_0, v_1, v_2) from three samples (sampling interval T) within the estimation interval, the estimated velocity trajectory, $\dot{\theta}_{est}$, can be expressed as

$$\dot{\theta}_{est} = \frac{30R}{T_f^5}\left\{(t+T_x)(t+T_x-T_f)\right\}^2 \tag{5}$$

where

$$T_x = -\frac{T}{\gamma}(\alpha \pm \sqrt{\alpha^2-\beta\gamma}) \tag{6}$$

$$T_f = \frac{T_x^2\sqrt{v_1}-(T_x-T)^2\sqrt{v_0}}{T_x\sqrt{v_1}-(T_x-T)\sqrt{v_0}} \tag{7}$$

$$R = \frac{v_0 T_f^5}{30T_x^2(T_x-T_f)^2} \tag{8}$$

Here, T_f is the total movement time, the time at which the speed switches to the assisted domain on the estimated bell waveform is taken as T_x, as shown in Fig. 4, where the horizontal axis represents time and the vertical axis represents the velocity. Since the actual time for the assisted reaching movement is $T_f - T_x$ and the time before T_x corresponds to an assisted mode, there exists a waveform that incorporates v_0, v_1 and v_2, even though the exact values it takes are not known. Also, R is the angular displacement $\theta_f - \theta_0$. Here, θ_f is the position at time T_f, θ_0 is the position at $t = 0$ of the estimated waveform, and α, β and γ are

$$\alpha = 4v_1 - \sqrt{v_1v_2} - 3\sqrt{v_0v_1} \tag{9}$$

$$\beta = 8\sqrt{v_0v_1} \tag{10}$$

$$\gamma = 2\sqrt{v_1v_2} + 2\sqrt{v_0v_1} - 4v_1 \tag{11}$$

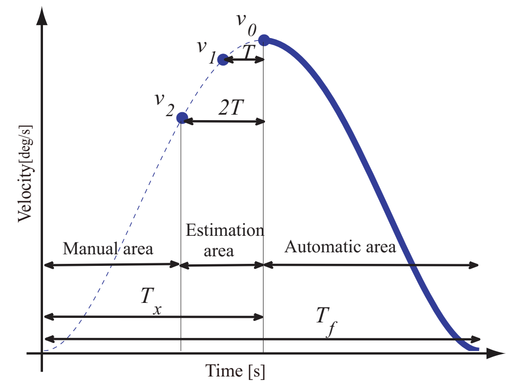

Fig. 4. Schematic of a estimated velocity trajectory

By using this method, a trajectory is estimated and flexion can be performed. However, there is the problem that after calculating the trajectory, it is impossible to take into account errors in the estimated target position or to avoid collisions with objects in the external environment. Also, as humans can be consider to perform control with two degrees of freedom by employing both feed-forward and feedback, rather than following the trajectory in a strict manner, they perform fine adjustments afterwards on the basis of visual and other sensory information.

Therefore, in the present research, the reach position is estimated on the basis of the minimum jerk criterion, and this position is regarded as the position of equilibrium of two virtual springs corresponding to the two opposing muscles for flexion and extension (as shown in Fig. 5), which apply a certain amount of force. The reach position estimated from (5) is used as the position of equilibrium of the opposing muscles. As a result, the springs exert force directed toward the equilibrium position, and this force can be expressed with Hooke's law as in (12). Here, θ_{eq} is the equilibrium position as obtained from the minimum jerk criterion. Also, the coefficient of elasticity is k_f for the flexor and k_e for the extensor.

$$F = k_f(\theta_{eq}-\theta) + k_e(\theta_{eq}-\theta) \tag{12}$$

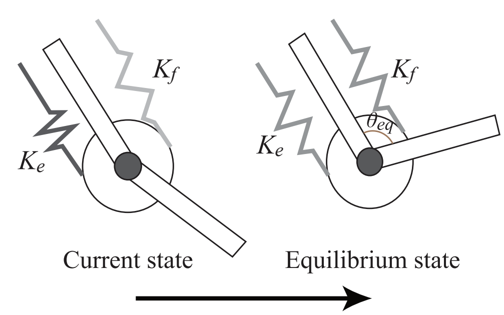

Fig. 5. Virtual springs used for modeling the upper limb

B. Variable coefficient of elasticity emulating the characteristics of muscles

Regarding the abovementioned virtual springs, the coefficient of elasticity is assumed to be variable, similarly to the case of muscles. When muscles contract, actin binds to proteins of the myosin group, which induces movement of the actin filaments. Myosins comprise the proteins that are responsible for the movement of muscles, and their size is less than several dozen nanometers[6].

Here, we implement a model of muscle movement in humans by using the structure of myosin molecules for exerting control. Upon estimating the reach position from the velocity trajectory based on the minimum jerk criterion mentioned in the preceding section, the estimated position is taken as the equilibrium position of virtual springs corresponding to the flexor and extensor muscles.

(14) presents the equation for the force generated with respect to the position of equilibrium. K_M is the largest value of the coefficient of elasticity.

$$K_e = K_M - K_M \exp\left(\frac{-|\theta_{eq} - \theta|}{10}\right) \tag{13}$$

$$F = K_e(\theta_{eq} - \theta) \tag{14}$$

Since the coefficient of elasticity is represented by an exponential function, this coefficient's value increases rapidly, and beyond a certain level of extension a coefficient of elasticity can be obtained that almost does not change.

C. Experimental verification

As a means of experimental verification, the device was worn by a participant with damage to the brachial nerve plexus, who was able to autonomously flex their arm to about 30[deg] from the maximum extension angle and further to about 50[deg] through passive motion. Therefore, the renge of motion of subject is 80[deg]. In the experiment, flexion and extension were tested by taking the maximum extension angle as a base. As the participant is limited in terms of autonomous movement range, it is impossible to determine whether the movements are performed freely. Therefore, we compared the case without assistance with the case where assistance was provided based on virtual springs by performing two tests on flexion, position retention and extension. In the unassisted case, the participant attempted to perform movements extending beyond the autonomous movement range. As the device was worn even in the case of no assistance, only impedance control was implemented. The results are presented in Fig. 6.

From top to bottom, the graphs show the input from the pressure sensor, the angle of the elbow joint, and the angular velocity of the elbow joint. The dotted lines represent the results obtained without assistance, and the continuous lines represent the results obtained with assistance based on virtual springs. Also, the colored region in the second graph represents the autonomous movement region for the participant. The experimental results indicate that although the participant was capable of autonomous flexion to about 25[deg], the presented assistance method allowed for flexion to about 45[deg]. In addition, although force was exerted in the position retention state in the absence of assistance, in the case where assistance was provided a position could

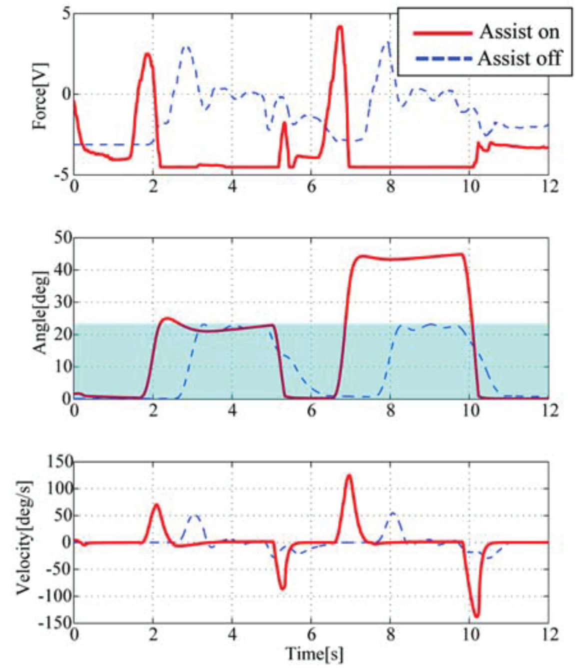

Fig. 6. Experimental test results for assisted movement of wearer with damage to the brachial plexus

be obtained without exertion of force. With these results, we demonstrated that by using their own will, wearers can freely perform flexion, position retention and extension.

IV. Conclusion

In the present research, we implemented flexion assistance for individuals with upper limb dysfunction caused by neuronal damage by utilizing a model using a coefficient of elasticity for emulating the characteristics of muscles. In an experiment with a participant with neuronal damage of the upper limb who was incapable of performing autonomous movement beyond a certain range of motion, the proposed system allowed the wearer to freely perform flexion, position retention and extension, even outside the autonomous movement range.

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