WEARABLE EXERCISE ROBOT WITH POWER ASSIST FUNCTION FOR WRIST REHABILITATION

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ABSTRACT
In this paper a wearable exercise robot with power assist function for wrist rehabilitation is proposed. A force model for the wrist mechanism is presented, and its control system for active exercise and power assist function is designed based on the force model. In experiments the performances of active exercise and power assist function are verified. From the experimental results we show a possibility of the wearable exoskeleton robot in wrist rehabilitation and wrist motion.

KEY WORDS
wrist rehabilitation, active exercise, power assist, force control

1. Introduction
Stroke is the loss of brain function due to disturbance in the blood supply to the brain by a cerebrovascular accident (CVA). In recent years, stroke has been the leading cause of adult disability and the second or third cause of death in developing countries [1]. It causes functional disabilities in one or more of the limbs, or disturbances in sensory function. It is known that repetitive rehabilitation with a therapist is an effective method for improving motor-functional disabilities in stroke survivors. Specialized occupational therapy and functional exercises are also helpful in improving body function. Such rehabilitation therapy requires a great deal of physical labor on the part of occupational and physical therapists, as well as great expenditure in terms of money and time. Therefore, the demand for robotic rehabilitation devices to assume part of the role of the therapist has been increasing.

In recent years, there has been a great deal of research related to upper-limb rehabilitation robots to assist stroke survivor in the performance of rehabilitation exercise [2-6]. In [2] an upper-limb exoskeleton device for shoulder, elbow and wrist rehabilitation was developed. And a hand rehabilitation robot to enable patients to stretch and strengthen muscles was developed [3]. However, none of these studies addressed the need to perform independent motion in the wrist and fingers. Subsequently, a robotic hand rehabilitation device with a multiples degree of freedom (DOF) was introduced. Ueki et al. [4] presented a hand rehabilitation robot with 16 DOF for the hand and 2 DOF for the wrist. In [5], a finger rehabilitation robot, not of the exoskeleton type, was introduced. However patients were required to visit a hospital equipped for rehabilitation exercise because most of the abovementioned device was fixed in a laboratory. In [6] an exoskeleton device to transmit force indirectly using the spiral-spring Bowden cables was proposed. Although the mechanism could enhance wearable property, the possible active motion was flexion only. Extension motion was not active type depended on the spring tensile force.

We proposed a wearable exercise device, DULEX-II capable of hand rehabilitation robot (see Figure 1) [7]. DULEX-II has 3 DOF for the motions of the wrist, the index finger, and a mechanism enclosing the other three fingers. But the wrist mechanism was impossible to perform active exercise and assist wrist function because the double-acting pneumatic cylinder for actuating wrist motion was only controlled in position without force.

In this paper, we propose a force control system to enable active exercise and power assist for wrist. Based on a force model of the wrist motion actuated by the cylinder, a force controller is implemented. Using an experimental setup capable of measuring the wrist force, the proposed system is verified. From the experimental results we show a possibility of the wearable exoskeleton device in the active wrist rehabilitation and power assist function.

2. DULEX-II
The mechanism of DULEX-II was designed based on kinematics analysis. The specifications for each part, such
Table 1 Specifications of Parts [degree].

<table>
<thead>
<tr>
<th>Parts</th>
<th>Items maximum position</th>
<th>minimum position</th>
<th>range of motion</th>
</tr>
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<tbody>
<tr>
<td>wrist</td>
<td></td>
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Figure 2. 3D model of DULEX-II

Figure 3. Modeling of wrist mechanism

Figure 4. Force model of pneumatic cylinder

as range of motion (ROM) and maximum position, are shown in Table 1. We designed a 3D model of DULEX-II as shown in Figure 2. The pneumatic cylinder is fixed on the forearm part so that the hand part, including the finger parts, can be rotated on the wrist joint. Then, the movement of the piston rod generates wrist extension and flexion motions. The prototype DULEX-II shown in Figure 1 has 504 g weight including all actuators. Because the pneumatic cylinder and the electric linear motor can generate a steady force, DULEX-II can assist hand functions as well as hand exercises for rehabilitation. The piston rod of the pneumatic cylinder is actuated by a pressure difference in the cylinder; the stroke length is 50 mm and the maximum possible pressure is 1 MPa. However, the pneumatic cylinder has no sensor to measure the position of the piston rod, so an external linear potentiometer to measure the position is needed.

2.1 Wrist Mechanism

Figure 3 shows the design model for the wrist mechanism, which is composed of 3-bar links. The wrist angle $\theta_w$ is controlled by the length $l_w$ of the piston rod in the pneumatic cylinder. This relation can be expressed by the following equation:

$$\theta_w = \beta + \cos \left( \frac{d_{w1}^2 + d_{w2}^2 - l_w^2}{2d_{w1}d_{w2}} \right) + \gamma - \pi$$  (1)

Figure 3 also shows a static model of wrist force. $w_F$ corresponding to the wrist joint torque is actuated by the cylinder output force $c_F$. The relation between $F_w$ and $c_F$ is expressed by the following equation:

$$F_w = d_{w1} c_F \sin(\theta_F) = f(c_F, \theta_F)$$  (2)

Here, $\theta_F$ is calculated by kinematics as the following equation.

$$\theta_F = \cos \left( \frac{l^2 + d_{w1}^2 - d_{w2}^2}{2l d_{w1}} \right)$$  (3)

In Eq. (3) $l_w$ is measured by a linear potentiometer.

2.2 Modeling of Pneumatic Cylinder

Figure 4 shows the modeling of pneumatic cylinder. The output force of the pneumatic cylinder, $F_c$, is generated by the difference of inner pressures, $p_1$ and $p_2$. In the equilibrium state, the output force $F_c$ is obtained by the following equation.

$$F_c(t) = k_A(p_2(t) - k_p p_1(t)) = g(p_1, p_2)$$  (4)

Here, $A$ is the left side area of the piston in the cylinder, and $k_p$ is the relative area rate of the right side as 0.84 [7].
And $\mu$ is a load factor in the cylinder, that was found by experiments. To simplify two input system in Eq. (4) we set one pressure to the atmospheric pressure according to the desired output force as follows. 

$$F_c(t) < 0, \begin{cases} p_1(t) = -\frac{1}{k_p \mu A} F_c(t) \\ p_2(t) = 0 \end{cases}$$

$$F_c(t) \geq 0, \begin{cases} p_1(t) = 0 \\ p_2(t) = \frac{1}{\mu A} F_c(t) \end{cases}$$

In Eq. (5) and (6) zero pressure means the atmospheric pressure.

### 3. Design of Control System

Figure 5 shows the pressure control system for the double-acting pneumatic cylinder. The inflow and outflow pressures of the cylinder are controlled by a one-way inflow valve. The inner pressure of the cylinder is measured by a pressure sensor. An air compressor supplies the air pressure, which is limited by a flow control valve. The piston rod of the cylinder is actuated by the pressure difference between the inner pressures, and the rod position is measured by a linear potentiometer attached in parallel to the cylinder.

Figure 6 shows the block diagram of the wrist force controller. When a target wrist force $F_w$ is given, the corresponding the goal pressure of the cylinder $F_c$ is first calculated by the inverse equation of the static model Eq. (2). And then pressure inputs $p_1$ and $p_2$ are obtained by using the conditional equations (5) and (6). The pressure controller was designed based on proportional-differential (PD) algorithm. Using the output pressure and the force model Eq. (4), the current cylinder force can be estimated. The final wrist force is also estimated by using the static model Eq. (2).

### 4. Experimental Results

The performance of the force controller based on the pressure controller was experimentally evaluated (see Figure 7). First, we verified the pressure control results when the input pressure $2.5 \text{ kgf/cm}^2$ was given at the initial pressure $1.5 \text{ kgf/cm}^2$ (see Figure 8). At 1.5 second, the control force changed to $2.5 \text{ kgf/cm}^2$, and then the output pressure was reached the target pressure after 7.5 second. Next we measured the output force to find the load factor $\mu$ in Eq. (4). The output force was measured by a push-pull gauge as shown in Figure 7. Figure 9 shows the measured results. From the experiments, the load factor $\mu$ was obtained as 0.85. Finally we evaluated the force controller performances. When the target wrist force was given from 15N to 45N at every 5N steps, the output wrist force was measured. And the results according to the different initial condition of the wrist angle $\theta_1$ were verified. In the experiments, the initial angle was set to 111° and 81°, respectively. Each experiment was performed five times in the same condition. As a result, the maximum error of the force control was less than 1N as shown in Figure 10.
We also evaluated the performance of active exercise function with five subjects (25±0.4 yrs) who were all male and healthy persons. Each subject performed wrist extension motion three times at every 5N steps when the anti-force for the extension exercise was given from 0N to 15N. The wrist extension force of user was verified to EMG signal measured on the extensor carpi radialis brevis muscle. In the evaluation, we utilized the analysis of variance (ANOVA) test that provides a statistically significant result between groups. In the test we used the peak EMG that is correspondent to the maximum voluntary contraction (MVC).

Figure 11 shows the results of ANOVA test, where ‘*’ and ‘**’ denote p-value <0.05 and p-value <0.005, respectively, and the black bar and the vertical line denote the mean and standard deviation of MVC. The measured data in Figure 11 shows that the mean of MVC increased in proportion to the anti-force, and the ANOVA test results also show that the anti-force to wrist extension motion makes the subjects generate more contraction muscle force. From these results, we can say that the proposed force control system can be used in active wrist rehabilitation.

The evaluation experiments for the power assist function was also performed with six healthy subjects (24±0 yrs) who were all male. As shown in Figure 12, the subject performed wrist flexion motion as holding a dumbbell of 3kg weight, but any external force except the dumbbell was removed. The assist level by the wrist mechanism was measured indirectly. We measured EMG from flexor carpi ulnaris muscle, and compared the MVC. The force for power assist was set to 0N, 10N, 20N, and 30N respectively. Each experiment performed four times at the same condition. Figure 13 shows the mean and standard deviation of MVC of six subjects. Using the ANOVA test, we verified the significant effectiveness statistically, where ‘*’ and ‘**’ denote p-value <0.05 and p-value <0.005, respectively, and the black bar and the vertical line denote the mean and standard deviation of MVC. From the experimental results, we can see the power assist function is effective to reduce muscle force for wrist motion.

5. Conclusion

In this paper, we proposed a wearable exercise robot with power assist function for wrist motion. First we established a static force model based on the designed wrist mechanism. Based on the force model of the wrist motion and the pneumatic cylinder, a force controller was designed. Using an experimental setup capable of measuring the wrist force, the performance of the exercise robot was verified. In the experimental results for force control, the error was less than 1N. From the experimental results showed that the proposed wearable exercise robot is feasible for the wrist rehabilitation.

We evaluated the performance of active exercise function with five subjects. The ANOVA test results showed a distinct significance that the anti-force to wrist extension is effective for active exercise. The evaluation experiments for the power assist function were also performed with six subjects. The results showed the
power assist function is effective to reduce the muscle force for wrist motion.

In rehabilitation exercise for patients muscle spasm is often occurred. Thus, it is important to prevent additional muscular injuries for applying the developed robot to a real rehabilitation exercise. Bio-feedback control is pertinent to the user safety issue, and it will be studied in future work.

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References