Development of Wrist Bending Rehabilitation Robot

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Abstract: This paper describes the wrist bending rehabilitation robot using a four-axis force/moment sensor. The robot can be used to exercise the wrist bending rehabilitation for severe stroke patients lying in bed wards or at home. The manufactured four-axis force/moment sensor which can detect two directional force Fx, Fy and two directional moment Mx, My, was attached to the developed rehabilitation robot and allows the rehabilitation robot to measure a bending force (Fx) exerted on a wrist, the signal force Fy and moments Mx, My which in turn allows the device to be used safely. The results of a characteristics test for the developed rehabilitation robot showed that it was safely operated while the wrist bending flexibility rehabilitation exercise was performed. Therefore, it is thought that the developed rehabilitation robot can be safely used with severe stroke patients.

1 INTRODUCTION

The numbers of patients with severe strokes are increasing rapidly in the world, and their wrists must receive rehabilitation exercises so that they can be used in everyday life. The wrist bending flexibility rehabilitation exercise bends the wrist in a counter-clockwise direction (right hand) or clock wise direction (left hand) based on the wrist, like with rehabilitation therapist, it conducts rehabilitation exercises until the patient starts feel pain, and then the robot pauses the exercise for a while (about 4s). It then bends back the wrist again in the opposite direction, and then pauses for a while. Rehabilitation therapists, nurses and physicians for rehabilitation find it very difficult to deal with the number of severe stroke patients and because of this some of the severe stroke patients don't receive adequate rehabilitation exercise. Therefore, the wrist bending rehabilitation robot has been developed for safe and adequate wrist bending rehabilitation and to ease the burden on rehabilitation therapists, nurses and physicians.

Pan developed three degrees of freedom rehabilitation robot for mild stroke patients sitting in a chair attached to a robot, that provided elbow rehabilitation exercise. Both Pan and Culmer did research on how to control the robot using the fuzzy theory. Kim developed the six degrees of freedom robot for upper limb rehabilitation of the minor stroke patients, and this robot was able to perform the rehabilitation exercises for mild stroke patients' upper limbs. Li developed an upper limb rehabilitation robot that could be used to exercise bending and straightening of a patients arm. The robot can measure the moment needed to the bend of the patient's arm and the control of the robot is performed using measured moment. Culmer developed a six degrees of freedom rehabilitation robot to rehabilitate patient's upper limb using two robots, and he researched the control of the robot for mild stroke patient's upper limb rehabilitation exercise.

These robots can perform the rehabilitation exercise for mild patients' wrists, but can't perform that of severe stroke patients' wrists. Thus, a wrist bending rehabilitation robot, such as rehabilitation therapist, that helps rehabilitate severe stroke patients lying in bed wards or at home by providing wrist rehabilitation exercises must be developed. The Rehabilitation robots must measure the moments of wrist rotated to counter-clockwise and clockwise, and be controlled using the measured moments. A four-axis force/moment sensor measures x, y directional force Fx, Fy and moment Mx, My, and it is composed of a body in order to reduce the size of the sensor in general. The four-axis force/moment sensor built into a wrist bending rehabilitation robot should be suitable in the size, with a rated capacity and price, and it should be easy

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to attach to the robot. Current developments of a multi-axis force sensor [Nagai, Kim and Kim] are not suitable for a wrist bending rehabilitation robot in terms of size, price and additional conditions. Therefore, the wrist bending rehabilitation robot needs to be developed for severe stroke rehabilitation lying in bed wards or at home.

In this paper, the wrist bending rehabilitation robot using a four-axis force/moment sensor was developed. The four-axis force/moment sensor was designed and fabricated for measuring the applied force (Fx) of patient's wrist and force Fy and moment Mx, My for a safe control of movement. And then a robot body was designed and manufactured. The characteristic test of a wrist bending flexibility rehabilitation exercise of a normal people and a stroke patient was carried out using the developed the robot.

2 DESIGN AND MANUFACTURING OF WRIST BENDING REHABILITATION ROBOT

2.1 Design and Manufacturing of Wrist Bending Rehabilitation Robot

Figure 1 shows the manufactured wrist bending rehabilitation robot, it was designed and manufactured to perform the rehabilitation exercise of a wrist for a stroke patient lying in a hospital ward. The rehabilitation robot was composed of a robot body, a hand fixing block, a hand fixture Velcro, an arm fixing block, an arm fixture Velcro, an up-down supporter, a wrist bending motor, a four-axis force/moment sensor, a high-speed controller and so on. The robot body was manufactured using aluminum square rods (size: 40mm×40mm), and its size is 800mm× 600mm ×400mm, and most of the robot’s parts were fixed to the robot body. The hand fixing block and the hand fixture Velcro were designed to be fixed to the patient's hand safely, and they were also fixed to the four-axis force/moment sensor that transmits the bending force (Fx) of the wrist bending motor to patient's wrist. The arm fixing block and arm fixture Velcro were designed to be fixed patient's arm safely, and they were also fixed to the robot body and the up-down supporter. The up-down supporter was designed to be adjusted the height of the patient's bed and to the height of the robot body with one side being fixed to the wrist bending motor and other side being fixed to the four-axis force/moment sensor. The wrist bending motor applies the bending force to patient's wrist, and it was fixed to the up-down supporter.

The four-axis force/moment sensor was designed and manufactured, it measures the bending force (Fx) applied to a patient's wrist during the rehabilitation exercise and also measures force Fy and moments Mx, My in case of emergency. The manufactured four-axis force/moment sensor is described in detail in the next section. The high-speed control system was manufactured to measure the forces and moments from the four-axis force/moment sensor, and to control the wrist bending motor with the measured force Fx, and also returns the robot to the initial position of the wrist bending motor using the measured force Fy and moments in case of an emergency situation.

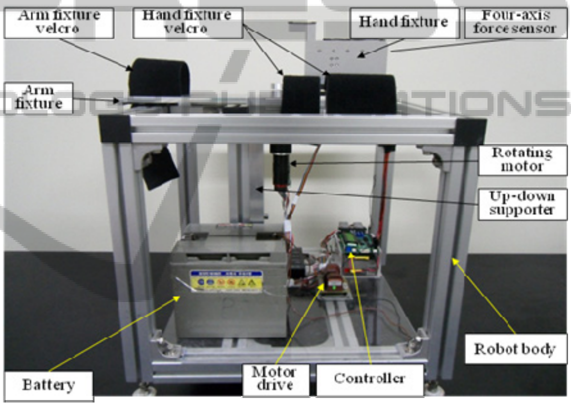

Figure 1: Manufactured rehabilitation robot for wrist bending exercise.

The wrist rehabilitation exercise using the wrist bending rehabilitation robot is conducted by, first, fixing patient's arm with the arm fixing block and the arm fixture Velcro. The patient's hand is then fixed to the hand fixing block and hand fixture Velcro, after which the stroke patient lies in bed. The robot bends the wrist counter-clockwise and clockwise by the rotating of the bending motor repeatedly, and the bending force exerted on the wrist (force Fx) is measured by the four-axis force/moment sensor. The robot is controlled with the reference of the measured bending force (Fx). In an emergency situation, the patient applies any force to the robot, the four-axis force/moment sensor measures forces Fx, Fy and moments Mx, My at the same time, and the high-speed control system stops the robot from using the forces and moments. The robot is then returned to the initial position of the motor.

2.2 Design and Manufacture of the Four-Axis Force/Moment Sensor

Figure 2 shows the structure of the four-axis force/moment sensor, and the sensor detects forces Fx, Fy, and moments Mx, My simultaneously. The sensor is composed of a force/moment transmitting block, F/M, two fixing block, F1 and F2, two moving block, M1 and M4, four parallel plate beam, PPB1~PPB4. PPB1 and PPB2 are for perceiving force Fx and moment My, and PPB3 and PPB4 are for force Fy and moment Mx. The sizes of the plate-beams composed of PPB1 and PPB2 are width b_1, thickness t_1, length l_1, those for PPB3 and PPB4 are width b_2, thickness t_2, length l_2. The size of the sensor is 104mm×20mm×20mm. Theoretical equations should be derived to determine the size of the sensor.

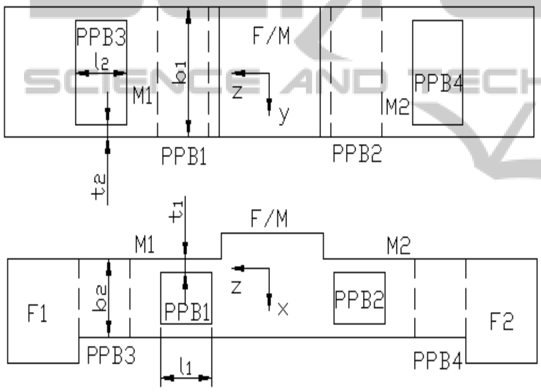

Figure 2: Structure of four-axis force/moment sensor.

Figure 3 shows the free body diagram of plate beams for a four-axis force/moment sensor under the forces Fx(or Fy). When the force Fx is applied to the point O of the force/moment transmitting block, force F_{Fxx} and moment M_{Fxy} are generated on the end of the plate-beam. The force F_{Fxx} and moment M_{Fxy} can be derived from the equations of force and moment equilibrium-condition $\sum Fx = 0$, $\sum Fy = 0$ and $\sum M_o = 0$ of the force/moment transmitting block and the moving block M1. And the equations ε_{Fx-U} and ε_{Fx-L} for analyzing the strains on the upper and lower surfaces of the plate-beams are derived by substituting the derived force F_{Fxx} and moment M_{Fxy} into the equation of bending moment $\varepsilon = M_z / EZ_{1P}$, and they can be written as

$$\varepsilon_{Fx-U} = \frac{3F_x}{2Eb_1h_1^3}(z - \frac{l_1}{2}) \tag{1}$$

where, E is the modulus of longitudinal elasticity.

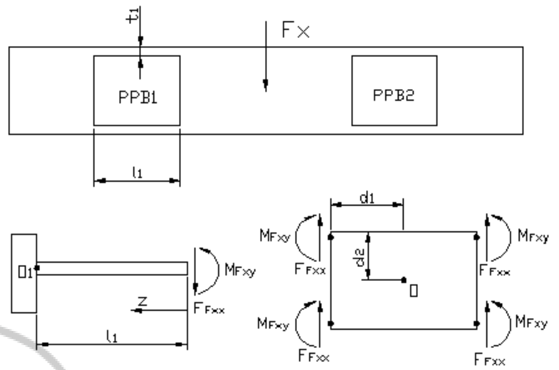

Figure 3: Free body diagram of plate beam for a four-axis force/moment sensor under the forces Fx(or Fy).

Figure 4 shows the free body diagram of plate beams for a four-axis force/moment sensor under the moment My(or Mx). When the moment My is applied to the point O of the force/moment transmitting block, forces F_{Myx} , F_{Myz} and moment M_{Myy} are generated on the end of the plate-beam. The forces F_{Myx} , F_{Myz} and moment M_{Myy} can be derived from the equations of force and moment equilibrium-condition $\sum Fx = 0$, $\sum Fy = 0$ and $\sum M_o = 0$ of the force/moment transmitting block and the moving block M1. And the equation of the rotational angle of force/moment transmitting block θ can be derived using forces F_{Myx} , F_{Myz} and moment M_{Myy} .

$$\theta = \frac{M_y}{\frac{48EI_1d_1}{l_1^3}(d_1 + \frac{l_1}{2}) + \frac{4A_1Ed_2^2}{l_1} + \frac{48EI_1}{l_1^2}(\frac{d_1}{2} + \frac{l_1}{3})} \tag{2}$$

And the equations ε_{My-U} and ε_{My-L} for analyzing the strains on the upper and lower surfaces of the plate-beams are derived by substituting the derived forces F_{Myx} , F_{Myz} and moment M_{Myy} into the equation of bending moment $\varepsilon = M_z / EZ_{1P}$ and the equation of tension and compression $\varepsilon = d_2\theta / l_1$, and they can be written as

$$\varepsilon_{My\text{-}U} = \frac{6t_1z}{l_1^3}(d_1 + \frac{l_1}{2})\theta) - \frac{6t_1}{l_1^2}(\frac{d_1}{2} + \frac{l_1}{3})\theta) + \frac{d_2\theta}{l_1} \tag{3}$$

The design variables of the modeled the four-axis force/moment sensor are the size of body, the rated output of each sensor, the rated forces and moments

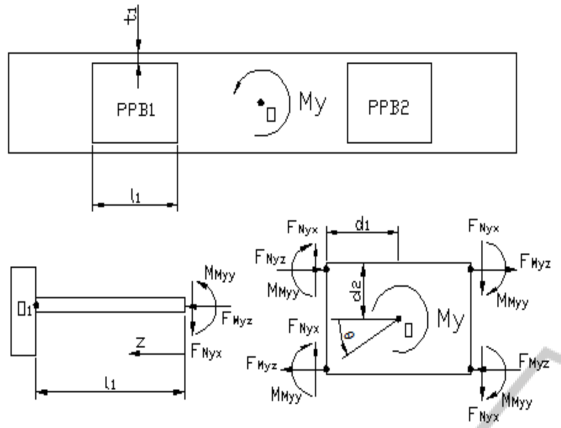

Figure 4: Free body diagram of plate beam for a four-axis force/moment sensor under the forces My(or Mx).

of each sensor, the size (width b_1, thickness t_1, length l_1) of plate-beams of PPB1 and PPB2, the size (width b_2, thickness t_2, length l_2) of plate-beams of PPB3 and PPB4. And, d_1 is the distance between the vertical center-line of the force/moment transmitting block and the right end point of PPB1, d_2 is the distance between the horizontal center-line of the force/moment transmitting block and the right end point of PPB1. The processing of the sensor design is as follow, first the size of sensor's body, the rated output of each sensor and the rated load of each sensor are determined. And then the width b_1, thickness t_1, length l_1, width b_2, thickness t_2, length l_2) of plate-beams are calculated by substituting the determined them into the equations (1) and (3).

Wheastone bridges are made for each sensor in the four-axis force/moment sensor. The rated strain of each sensor under each rated force or moment is determined from the strain values of the attached strain-gages to each sensor. Total strain of Wheastone bridge can be calculated as following equation.

$$\varepsilon = \varepsilon_{T1} - \varepsilon_{C1} + \varepsilon_{T2} - \varepsilon_{C2} \quad (4)$$

where, ε is total strain from Wheastone bridge, ε_{T1} is strain of a tension strain-gage T_1, ε_{C1} is strain of a compression strain-gage C_1, ε_{T2} is strain of a tension strain-gage T_2, ε_{C2} is strain of a compression strain-gage C_2.

And, the rated output can be calculated as below equation.

$$\frac{E_o}{E_i} = \frac{1}{4} K\varepsilon \quad (5)$$

where, E_i is the input voltage of Wheastone bridge, E_o is the output voltage of Wheastone bridge, K is the factor of strain-gage (about 2.0), ε is total strain gotten from equation (4).

The rated outputs of the variables for designing the four-axis force/moment sensor is determined by about 0.5 mV/V respectively, the rated force and moment of each sensor of the four-axis force/moment sensor are Fx=Fy=100N, Mx=6Nm and My=7Nm, the size of the sensor is 104mm×20mm×20mm, the attaching locations of strain-gages in length-direction is 1.5mm from the end of the plate-beam, the attaching locations of strain-gages in width-direction is on the center line of the plate-beams, and the rated strain at the attaching location of strain-gage is about 250 $\mu m/m$. The sizes of sensing elements of the four-axis force/moment sensor are determined by substituting the determined variables into equations (1) and (3). The lengths l_1 and l_2 are 10mm respectively, the widths b_1 and b_2 are 20mm and 12mm, the thicknesses t_1 and t_2 are 1.14mm and 1.36mm, the distance d_1 and d_2 are 12mm and 5.34mm respectively. The material of the sensor id Al 2024-T351.

Figure 5 shows the attachment locations of strain gages on each sensing element of four-axis force/moment sensor. The attaching locations for each sensor in the four-axis force/moment sensor were determined in consideration of the results of theoretical analysis. The attaching locations of strain-gages for Fx sensor are S1~S4, those for Fy sensor are S5~S8, those for Mx sensor are S13~S16, those for My sensor are S9~S12. The attaching location of each strain-gage is 1.5mm from the end of plate-beam in the length-direction, and that in the width-direction is the center line of plate-beam. These locations were determined in consideration of the interference error 0% calculated by equation (4). The rated strains of each sensor in the four-axis force/moment sensor at each attachment location of strain-gages were calculated by theoretical analysis. The rated strains for Fx sensor and Fy snsor were 992 $\mu m/m$, and those for Mx sensor and My sensor were 992 $\mu m/m$ and 968 $\mu m/m$ respectively. The maximum error of each sensor was less than 3.2%, reflecting the fact that the sensing element is 0.01mm thick, taking the manufacturing processing into consideration.

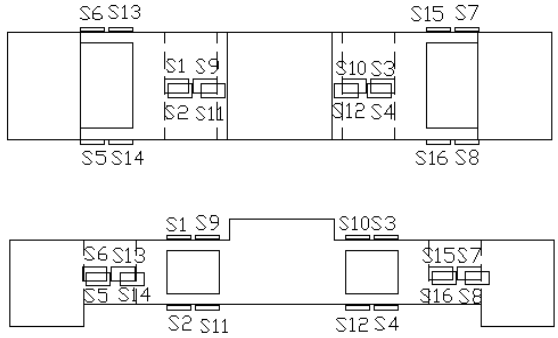

Figure 5: Attachment locations of strain gages on each sensing element of four-axis force/moment sensor.

The four-axis force/moment sensor was fabricated by using the bond (M-200) and the strain gauges (N2A-13-S1452-350, made in Micro-Measurement Company, gauge constant 2.03, size 3×5.2mm), and constructed Wheatstone bridge. Figure 6 shows a photograph of the manufactured four-axis force/moment sensor, the rated forces of Fx sensor and Fy sensor are each 100N, and the rated moments of Mx sensor and My sensor are each 6.00Nm and 7.00Nm. The size of the four-axis force/moment sensor is 104mm×20mm×20mm. The characteristic test of the manufactured four-axis force/moment sensor must be carried out to get the rated output, the repeatability error, the non-linearity error and the interference error of each sensor. The characteristic test was performed with a multi-axis force/moment sensor calibration system [Kim] and a measuring device (DMP40).

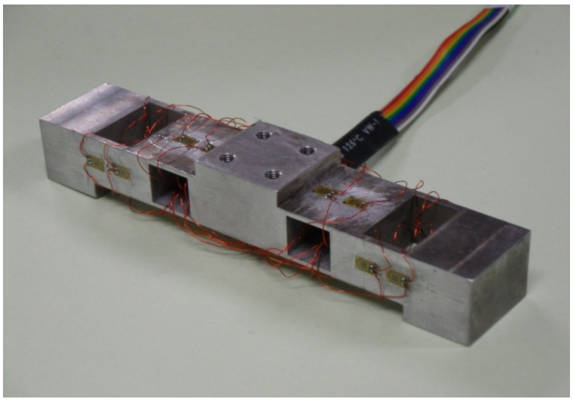

Figure 6: Manufactured four-axis force/torque sensor.

In order to detect the rated output of each sensor and the interference error of the four-axis force/moment sensor, the moment and the force from each sensor was measured under the rated force and the moment of each sensor and it was repeated three times, and the rated output of each sensor was derived by averaging the values. Table 1 shows the rated output from theoretical analysis and characteristic test of each sensor of four-axis force/moment sensor. The rated outputs from theoretical analysis were by substituting the gage factor 2.03 of strain-gage and the calculated rated strain from equation (4) into the equation (5). The rated outputs of Fx sensor, Fy sensor, Mx sensor and My sensor were 0.4927mV/V, 0.5145mV/V, 0.5084mV/V and 0.4893mV/V respectively. The maximum error of the rated output from theoretical analysis and characteristic test was less than 2.21%. Table 2 shows the interference error of each sensor of four-axis force /moment sensor, The maximum interference error of the four-axis force/moment sensor was less than 0.96%.

In order to get the repeatability error and the non-linearity error of each sensor, the force and the moment from each sensor was measured under the force and the moment 10%~100% of the rated force and the moment with 10% step of each sensor and it was repeated three times. The maximum repeatability error and the maximum non-linearity error of each sensor were less than 0.03% respectively. Therefore, the four-axis force/moment sensor manufactured in this paper is similar to the multi-force sensors previously developed [Kim and ATI INDUSTRIAL AUTOMATION] in level of the errors. Thus, it is thought that the manufactured four-axis force/moment sensor can be used for the wrist bending rehabilitation robot. The developed four-axis force / moment sensor is suitable for use in rehabilitation robotics, because it is inexpensive, and its size is 104×20×20mm.

Table 1: Rated output from theoretical analysis and characteristic test of each sensor of four-axis force /moment sensor.

Sensor	Rated output (mV/V)		
	Theo.	Exp.	Error(%)
Fx	0.5034	0.4927	2.13
Fy	0.5034	0.5145	-2.21
Mx	0.5034	0.5084	0.99
My	0.4913	0.4893	0.41

Table 2: Interference error of each sensor of four-axis force /moment sensor.

Sensor	Interference error(%)			
Force	Fx	Fy	Mx	My
Fx=100N	-	0.23	0.52	0.96
Fy=100N	0.31	-	0.27	0.38
Mx=6Nm	0.48	0.18	-	0.62
My=7Nm	0.59	0.31	0.24	-

The four-axis force/moment sensor with the high-speed control system was calibrated using the multi-axis force/moment sensor calibration machine [Kim] to measure the forces and moments. The calibration was performed as follows: first, in order to calibrate Fx sensor of the four-axis force/moment sensor, the calibration machine applied the rated force of Fx=100.0N to x-direction, and the indicated value of Fx sensor was adjusted to 100.0N (resolution: 0.2N). The Fy sensor, Mx sensor and My sensor were calibrated as that of the Fx sensor, and they were adjusted to 100.0N (resolution: 0.1N), 3.00Nm (resolution: 0.01Nm), 5.00Nm (resolution: 0.01Nm) respectively.

3 THE CHARACTERISTIC TEST OF A WRIST BENDING REHABILITATION ROBOT AND ITS FINDINGS

3.1 Characteristic Test of Wrist Bending Flexibility Rehabilitation Exercise

Figure 7 shows the characteristic test for the wrist bending flexibility rehabilitation exercise using the wrist bending rehabilitation robot. The wrist bending flexibility rehabilitation exercise is performed as follows; first, a person's wrist and arm are safely fixed using the fixtures and Velcro. The reference bending force and the reference bending angle (the measured bending angle add 5°) in counter-clockwise and clockwise are then measured and are inputted into the high-speed control system. The initial position (the reference angle (0°)) of the hand fixture and person's right hand is that the palm is straight in the axial direction of the arm and vertical with the ground, when person was lying in bed. The method of wrist bending flexibility rehabilitation exercise is as follows; first, the right hand is bended to counter-clockwise from the bending force of 0.0N (the initial position) to the reference bending force using the motor attached to the robot, the robot is controlled with the reference bending force for about 4s. Then it is rotated to clockwise like counter-clockwise. Such a process carried out continuously.

Figure 8 shows the results of the characteristic test for the wrist bending flexibility rehabilitation exercise using the wrist bending rehabilitation robot. The two forces and two moments are outputs from the four-axis force/moment sensor during the wrist bending flexibility rehabilitation exercise. The force Fx is the generated force that the robot pushes the palm or the back of hand, The force Fy is the generated force that the hand presses the hand fixing block in upward and downward, the moment Mx is the generated moment that the end of fingers or the part of hand presses the hand fixing block in upward and downward (y-direction), and the moment My is the generated moment that the end of fingers or the part of hand presses the hand fixing block left and right direction (x-direction). As the results of the measurement tests of subject, the reference bending force (Fx) and the reference angle in counter-clockwise were -14.1N and 90.5° respectively. And in clockwise, they were each 18.8 and 89.3°. Therefore, the reference bending force and the reference bending angle (the measured bending angle add 5°) in counter-clockwise and clockwise are then measured and are inputted into the high-speed control system.

As shown in Figure 8, the reference wrist bending forces (Fx) were applied to subject's right hand in counter-clockwise and clockwise during the

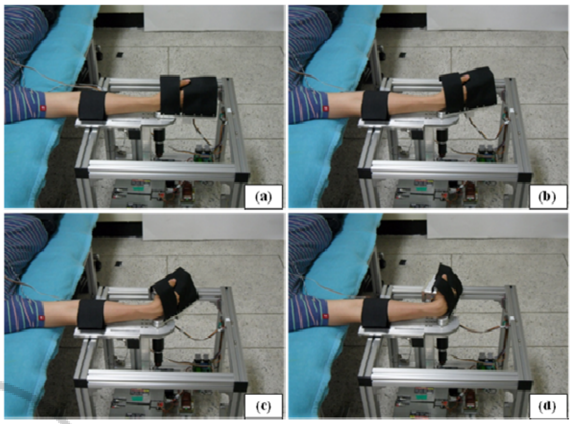

Figure 7: Photographs of characteristic test for wrist bending flexibility rehabilitation exercise using the wrist bending rehabilitation robot (right hand).

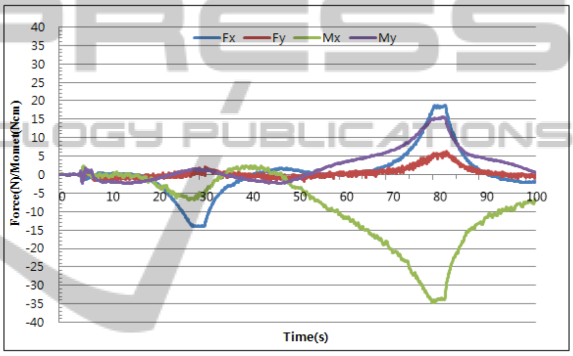

Figure 8: Graphs of characteristic test for wrist bending flexibility rehabilitation exercise using the wrist bending rehabilitation robot (right hand).

wrist bending flexibility rehabilitation exercise, and then the PI control at the reference bending force was performed for about four seconds. The force Fy at reference bending force in counter-clockwise was 2.5N, and 6.2N in clockwise. The moment Mx at reference bending force in counter-clockwise was -0.07Nm(-7Ncm), and -0.35Nm(-35Ncm) in clockwise. The moment My at reference bending force in counter-clockwise was 0.02Nm(2Ncm), and -0.15Nm(-15Ncm) in clockwise. The generated forces and moments in clockwise were greater than those in counter-clockwise, because the wrist withstand greater force in counter-clockwise (bending to backward). And the generated force Fy and the moments Mx, My were that the fixing block pushes the palm to the end of finger direction.

Thus, the Fx sensor of the four-axis force/moment sensor attached to the robot can be used to control for performing the wrist bending rehabilitation exercise by measuring the bending force (Fx) of wrist, and the Fy sensor and Mx sensor can be used to sense the fixing situation of patient's arm during the wrist bending rehabilitation exercise by measuring forces Fx, Fy and moments Mx, My.

3.2 Characteristics Test of Wrist Bending Flexibility Rehabilitation Exercise of Severe Stroke Patient

The characteristics test of the wrist bending flexibility rehabilitation exercise was carried out to confirm applying the wrist bending rehabilitation robot for severe stroke patient. The characteristic test was carried out at YESON Rehabilitation Hospital, and a severe stroke patient who was almost unable to move the right hand participated in the test. She received her wrist bending flexibility rehabilitation exercise using the wrist bending rehabilitation robot for thirty minutes each day.

Figure 9 shows the stroke patient's characteristic test for the wrist bending flexibility rehabilitation exercise using the wrist bending rehabilitation robot. Figure 10 shows the outputs of the two forces and the two moments from the four-axis force/moment sensor in a severe stroke patient's wrist bending flexibility rehabilitation exercise using the wrist bending rehabilitation robot(for three days). At the results of rehabilitation exercise for eight days, the reference bending forces in counter-clockwise and clockwise were -5.4N and 9.4N, and the reference bending angles were 48.23° and 47.97° respectively. The bending force after eight days was 3.1N bigger than after three days in counter-clockwise, and that in clockwise was 4.5N bigger. And the bending

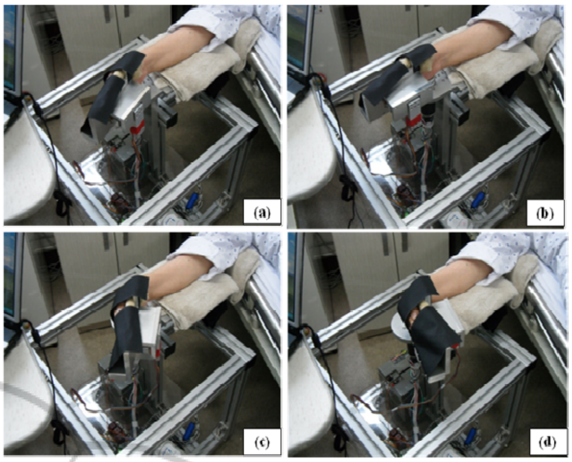

Figure 9: Photographs of stroke's characteristic test for wrist bending rehabilitation exercise using the wrist bending rehabilitation robot (right hand).

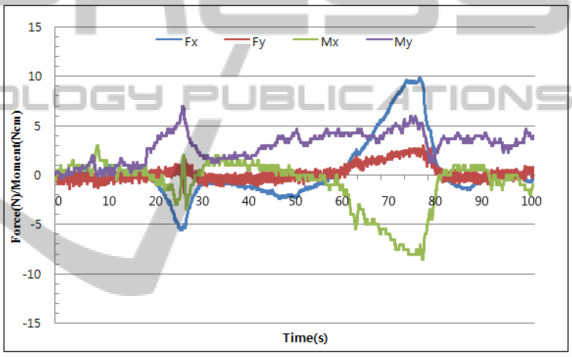

Figure 10: Graphs of stroke's wrist bending flexibility rehabilitation exercise using the wrist bending rehabilitation robot (right hand).

angle after eight days was 0.72° bigger than after three days in counter-clockwise, and that in clockwise was 3.33° bigger. The reference bending forces from the sensor and the reference bending angles were determined when the robot rotated the patient's wrist until she felts pain in counter-clockwise and clockwise in the everyday. To reveal bigger moment Mx=-0.09Nm(9.00Ncm) was fixed to the patient's wrist axis in discord to the central axis of the hand fixture, and the part of wrist pushed the wrist fixing block as shown in Figure 9. It is that the four-axis force/moment sensor was composed of a body.

4 CONCLUSIONS

In this paper, the wrist bending rehabilitation robot using the four-axis force/moment sensor was developed. The four-axis force/moment sensor of the wrist bending rehabilitation robot was designed and manufactured, and the interference error of the four-axis force/moment sensor and the maximum repeatability error and the maximum non-linearity error of each sensor are similar to that of the developed sensor [Kim and ATI INDUSTRIAL AUTOMATION]. Thus, the four-axis force/moment sensor can be used for the wrist bending rehabilitation robot. In the characteristic test of the wrist bending flexibility rehabilitation exercise, the robot was accurately operated with the reference bending force in counter-clockwise and clockwise motions. The robot was safely operated when severe stroke patient received the wrist bending flexibility rehabilitation exercise. Therefore, it is thought that the developed wrist bending rehabilitation robot can be applied to severe stroke patient for the wrist bending flexibility rehabilitation exercise.

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