Intention Identification and Control Strategy of the Upper Limb Exoskeleton Robot

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Abstract: This study proposes a rehabilitation robot for upper limb exoskeleton providing power assistance to the upper limb activities. It provides people on rehabilitation a multi-functional and customized tool. The important features of this product are to correctly and quickly identify the user's intention through sensors' signals and to complete the appropriate needed power through the drive system of the mechatronic system. In particular, according to the user's recovery situations, the robot can provide three kinds of rehabilitation control strategies, namely, active control, semi-active control and passive control. By integrating the input requirements of sensors and loading conditions of user under various usage conditions, the threshold values of the critical parameters will construct and will serve as the reference for adjusting parameters of controller of the robot so that the stability of control system and the comfort of user are advanced. This study focuses on the bi-axial control arm exoskeleton and designed a flexible pressure sensor as the main bi-axial pressure sensors to sense the motion directions of the human arm. The analog signals of the flexible pressure sensor are converted into digital signal through MCP3208 and used BC2 microcomputer system to analyze and derive the torque distribution of the two joints. It allocates the power to the different joints according to the torque distribution to establish a complete arm exoskeleton control system and successfully drive the arm exoskeleton operation. It also can produce a prototype to verify the intention of a person through the sensor signals. By coordinating the drive torque of the human upper limb force and exoskeleton robot motor, we can keep the small interference force to assist the user to have a smoother rehabilitation motion.

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1. Introduction

Exoskeleton robots have been widely applied in military and civil fields. In military aspect, the combat effectiveness of troops is increased significantly as exoskeleton robots provide soldiers with a higher ability of carrying loads, a faster speed of walking and running, and a longer time of endurance. In civil aspect, exoskeleton robots can be used in the occasions such as mountain-climbing, firefighting, and disaster relief where the use of cars is incapable but the carrying of heavy goods, materials, and accouterments is needed. In medical aspect, exoskeleton robots can not only help the physically disabled, the elderly, and amyosthenia patients to walk, but can also compel them to rehabilitate themselves.

The purpose of this paper is to measure the bi-axial pressure value through only a point on the arm. It aims to calculate the current pressure angle through the pressure values of the two axial by using the pressure angle and the tangent of the sensor of the different joints to determine and compute the shoulder and elbow joint steering ratio and relative speed and construct a complete arm control system so that each of the arm exoskeleton can be very close to the user's needs. In the sensor pressure signal, this paper combined the pressure sensor into a two-axis pressure sensor. The device is connected to the human forearm to measure both the axial pressure on the forearm and is coordinated with the angle sensor to read each joint angle in the exoskeleton. MCU can calculate the joint angle of each joint according to the rotation direction and relative velocity relationship

through both axial pressure and joint angles and it drives the arm exoskeleton movements. First, as shown in the research flowchart in Figure 1, the location to capture signal is in the forearm. To calculate the pressure needs, it should be able to read at least two axial pressure signal to determine the angular orientation. Thus, we need to define the sensing direction of the two axes in order to correctly determine the pressure angle. As shown in Figure 2, the signal in the parallel direction of the forearm is defined as the X-axial signal while the signal in the perpendicular direction of the forearm is defined as the Y-axial signal.

The related researches as follows: Li proposed a three degrees of freedom arm exoskeleton and carried out the kinematics analysis and modeling of the arm exoskeleton based on the movement parameters of various joints [1]. According to clinic application demands, Li made researches on system design, surface electromyogram control, force control of rehabilitation training robot for hemiplegic upper limbs and rehabilitation training strategies [2].

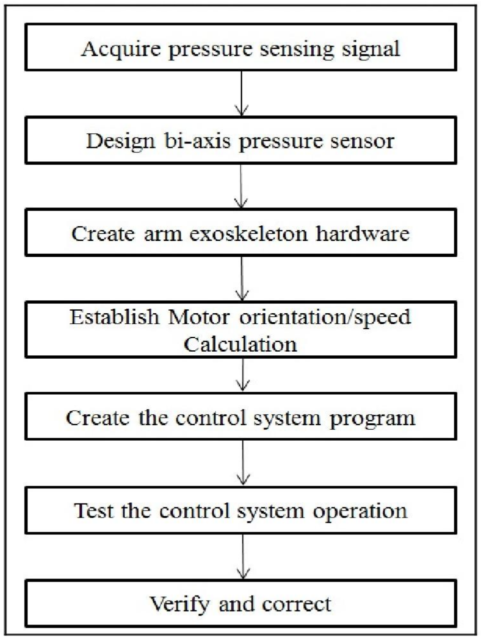

Figure 1. Research flowchart

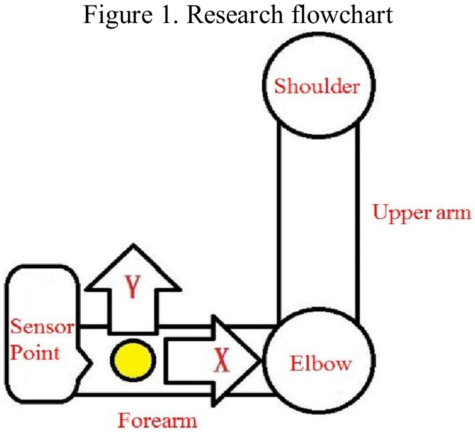

Figure 2. Bi-axial definition schematic diagram of the sensor points

Sun et al. carried out the theoretical analysis and the technical realization of the perceptual system of the wearable power assist leg (WPAL). A multi-sensor perceptual system, which includes the leg reaction force sensors, the ground reaction force sensors, and the joint angle sensors, was designed based on the analysis of the need for interactive information to control the WPAL. A related experiment indicated that the system is stable and provides a safeguard for the control of WPAL [3]. In MCU programming aspect, this paper has referred to the book authored by Zhong [4]. Lum et al. and Burgar et al. developed a series of Mirror-Image Motion Enabler (MIME) robotics. These series of robotics can be dived into three generations. The 1st generation can perform two degrees of freedom simple articulation motion, including bending and stretching of elbow, and whirling forward and whirling backward of forearm. The 2nd generation can realize the planar motion of forearm. The 3rd generation can realize the three dimensional motion of forearm [5-9]. Reinkensmeyer et al. and Kahn et al. developed an Assisted Rehabilitation and Measurement Guide (ARM Guide), which has three degrees of freedom, including yaw, pitch, and reach. The first objective in developing the ARM Guide was to provide an improved diagnostic tool for assessing arm movement impairment after brain injury. The second objective in developing the ARM Guide was to provide a therapeutic tool for exploring the effects of active assist therapy [10-11]. He et al. and Sugar et al. invented a wearable device for Robotic Upper Extremity Repetitive Therapy (RUPERT), which has four actuated degrees-of-freedom driven by compliant and safe pneumatic muscles on the shoulder, elbow, and wrist. The sensors feed back position and force information for quantitative evaluation of task performance. The device can also provide real-time, objective assessment of functional improvement [12-13].

2. Research Methodology

The exoskeleton structure studied in this paper is a two-degree-of-freedom planar arm structure, composing of a shoulder, an upper arm, an elbow and a forearm. As shown in Figure 3, there are two different tangent directions, the tangent of the shoulder on the sensor during rotation and the tangent of the elbow on the sensor during rotation. This paper used the pressure angle and the angle of the potentiometer calculated from the X-axis and Y-axis measured by the two axis of the pressure sensors of these two tangents to calculate the shoulder and elbow joint steering and relative speed ratio.

2.1 Steering/Speed Distribution

The operation control of the arm exoskeleton is based on the operating method of the pressure ρ as shown in Figure 4. Thus, the calculated rotation direction and speed ratio between the two joints of the arm exoskeleton occupied important proportions in the entire control system. The steering speed distribution of the arm exoskeleton can be divided into three parts, namely the angle γ、ϕ and θ and proportion.

As shown in Figure 4, when the pressure ρ is located between the angles -A to B, the range of angles is ϕ. The angle Φ-θ uses the elbow joint (B) as reference axis. Thus, the angle of -A to the pressure index ρ is θ and if joint(A) is used as the reference axis, the angle of B is to ρ is Φ-θ. To calculate the proportion occupied by angle θ in angle Φ, we need to compute the value of θ and Φ first. Since A to-A is a straight line, the angle (angle Φ) of -A to B can be obtained by the following equation.

$$\Phi = 180^{\circ} - \gamma \quad (1)$$

Angle θ can be determined by equation (2).

$$\theta = 90^{\circ} - \gamma + \alpha \quad (2)$$

In the equation above, angle α is the angle between pressure (ρ) and the exoskeleton of the forearm.

After obtaining angle Φ and angle θ, calculate the proportion of the elbow speed

$$b\% = \frac{\theta}{\Phi} \times 100\% \quad (3)$$

In the formula above, $b\%$ is the rotation speed percentage of the elbow.

In contrast, the rotation speed percentage of the shoulder can be obtained by the formula shown below:

$$a\% = 100\% - b\% \quad (4)$$

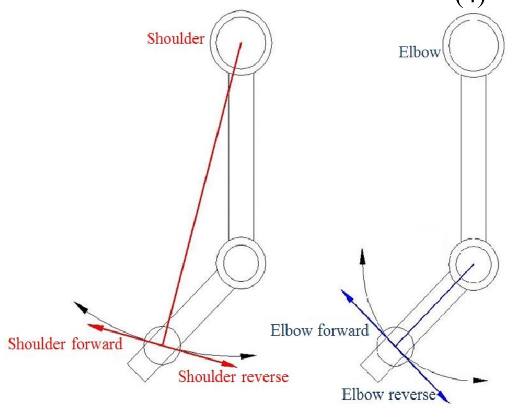

Figure 3. Tangent direction diagram of the rotation of each joint

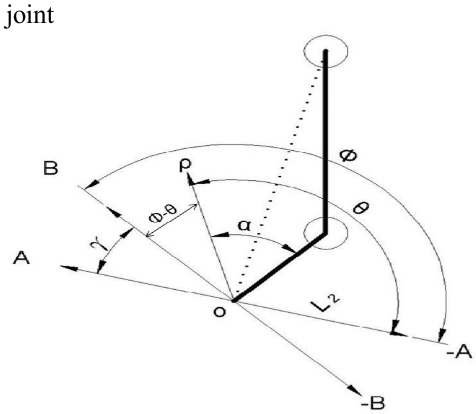

Figure 4. The schematic diagram of the exoskeleton arm angle

3. Research Procedure

3.1. Two-axis Pressure Sensor

This paper used two pieces of Flexiforce sensors as the main component. To transmit the pressure caused by the movement of the arm to the pressure block of the Flexiforce sensor, a L-shaped pressure sensor is designed as shown in Figure 5.

3.2. The Structure of the Arm Exoskeleton

The main structure of the arm exoskeleton is composed of fixed shoulder plate, arm board, the forearm plate and motor. The fixed shoulder plate, arm board and forearm boards are cut from the PP material. The shoulder drive system is shown in Figure 6, and the two-axis pressure sensor system is shown in Figure 7.

3.3 Circuit of the Control System

The flowchart of the overall process control system of the arm exoskeleton is shown in Figure 8. It is divided into a sensing structure of the arm exoskeleton, the central control processor, the driver blocks of the exoskeleton and the MCU terminal display.

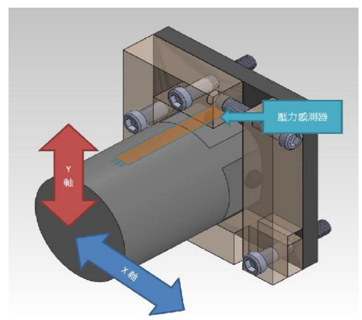

Figure 5. Schematic diagram of the L-shaped pressure sensor

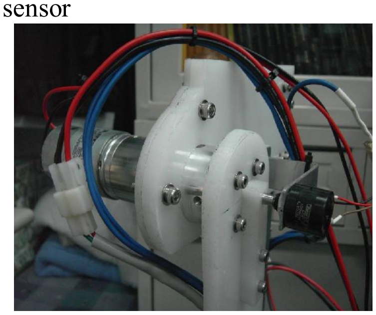

Figure 6. The shoulder motor and the potentiometer

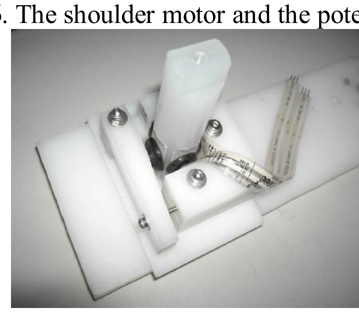

Figure 7. The assembly diagram of the two-axis pressure sensor

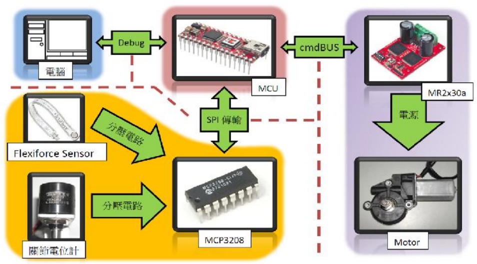

Figure 8. Flowchart of the system control hardware

If the BASIC Commander board computer needs to read the converted digital data of the MCP3208, it must go through SPI communication method and MCP3208 communication. Because innoBASIC™ Workshop does not have a command for SPI communication subprogram. This paper used the SPI communication format of the MCP3208 datasheet to the subprogram.

3.4 Pressure Sensor

The bi-axial pressure sensor can read the pressure value of the the X-axis and Y-axis, but it's not sure if the value of the bi-axial is the same with the pressure angle after conversion. Thus, it must be verified through the experiment. The test method is to place an angle plate in the bi-axial pressure sensor and then, fixed the X-axis and the Y-axis of the bi-axial pressure sensors into position (as shown in Figure 9). Set the pressure angle measurement point on the bi-axial pressure sensor and dig holes in the angle plate. Set the single line on the pressure axis of the bi-axial pressure sensor and pass it through the hole of the angle plate. Then, the force is applied to the single line to give the pressure on a pressure axis a fixed direction.

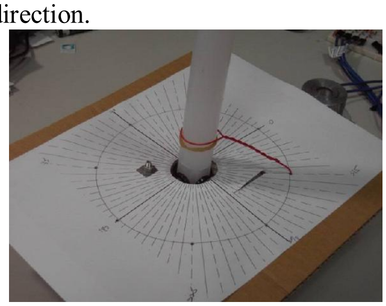
Figure 9. Test charts of angles

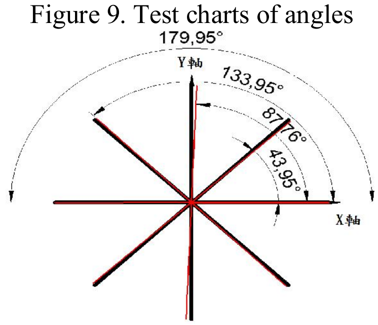

Figure 10. Point coordinates of the first test of angles

The validation work is a continuous improvement of the flatness, pressure sensor placement and angle. After several amendments in the angles, the error value can be adjusted to 0.1 degrees, as shown in Table 1. The angle coordinates of the corrected test shown in Figure 10 shows that the error has been reduced to an acceptable range.

4. Results and discussions

4.1. Torque Distribution of the Drive Motor

Equation (1) to equation (4) derived the intention pressure vector index of the bi-axial pressure sensor is converted into ρ vector and obtain the current angles α and β according to the lever length and angle of the potentiometer. ρ vector divides the tangent vector of the elbow into B and -B direction. The tangent vector of the shoulder is divided into A and -A direction. We determine the distribution principle of the motors' torque load according to the intention value of the ρ vector so that the arm movements can obtain the appropriate assistance from the motor torque without any interference. Figure 11 and Figure 12 shows the torque distribution example in an angle of 45°. Table 2 uses separately the direction angle ρ of the different intentions of the arm as example. When α=45°, α=90° and α=135°, the rotation distribution between the motors of the shoulder and elbow can serve as a reference for future software and hardware design.

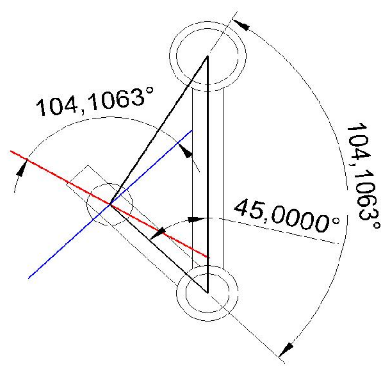

Figure 11. The schematic diagram of the elbow at 45°

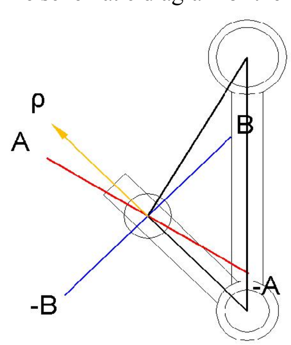

Figure 12. The schematic diagram of the elbow at 45°

Table 1. Test data of the angle after correction

NO. of time/Angle (degree)	360	45	90	135	180	225	270	315
1	2	43	89	135	180	224	268	314
2	1	46	92	136	179	226	270	316
3	360	45	91	136	182	225	269	315
4	1	44	88	134	181	224	270	315
5	359	46	89	135	181	225	271	314
6	358	47	89	136	178	226	270	315
7	360	45	90	134	179	224	271	316
8	1	44	92	135	178	226	270	314
9	1	44	91	134	178	224	270	314
10	359	46	92	136	182	226	271	315
11	2	45	89	135	178	225	269	315
12	1	44	88	136	182	226	268	315
13	1	43	89	135	180	226	269	314
14	360	46	91	134	181	224	270	314
15	1	44	91	135	181	226	271	316
16	359	45	89	136	178	224	270	314
17	358	44	91	135	181	225	270	315
18	1	46	92	136	178	224	271	316
19	2	45	88	135	181	225	270	316
20	359	46	90	134	180	226	271	315
Mean (degree)	360.3	44.90476	90.04762	135.09524	179.9048	225.0476	269.9524	314.9048
Error	-0.3	0.095238	-0.04762	-0.0952381	0.095238	-0.04762	0.047619	0.095238

Table 2. The motor torque distribution of different pressure sensing vector ρ

α	Parameter		
	L3	γ	ψ
45°	24.79	104.11	104.11
90°	38.47	62.10	117.89
135°	48.43	29.76	150.24
	Parameter		
α	θ	β%	α%
45°	14.11	13.55	86.45
90°	27.90	-23.66 (reverse)	76.33
135°	60.24	40.09	59.91

4.2. The Function Track of the Arm Exoskeleton

In order to understand the state of motion of the arm exoskeleton more clearly, the actual control arm exoskeleton made several actions, as shown in Figure 13, such as lifting of the arm, linear motion, lifting of the forearm, bending of the forearm (Figure 14), move in quadratic motion and move in circular motion. Record the data of these actions and draw its trajectory to see if there are any movements of the arm exoskeleton that are not moving smoothly.

BC2 has a command called Debugfile. It can save the data we outputted in the terminal window as txt files. Therefore, we can use this command to save the arm exoskeleton operation data into a text file and then use Microsoft Excel to draw the diagram and can even use graphics to view the trajectory of the arm exoskeleton.

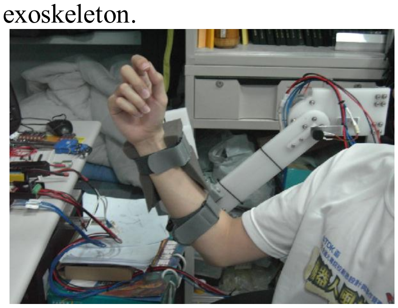

Figure 13. Actual installation diagram of the arm exoskeleton

Using the bending and lifting of the forearm as an example, the rotation arrow, as shown in Figure 14, is the movement trajectory. The actual trajectory of the arm is shown in Figure 15. In comparison of the normal error value between the two positions, the maximum error is less than 5mm. With regards to 180 mm forearm, the relative error is less than 4%. For the person under rehabilitation and for the rehabilitation centers, this result is quite important.

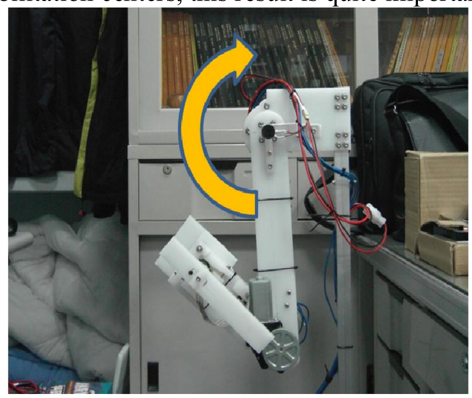

Figure 14. Schematic thrajectory of the bending and lifting of forearm

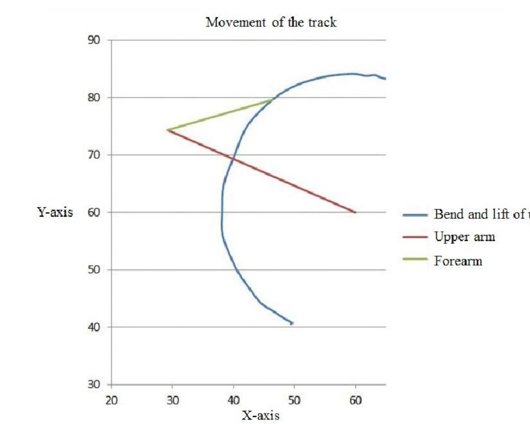

Figure 15. The trajectory drawing of the bending of the forearm

5. Conclusion

According to the theory and experimental results, the bi-axis pressure sensor reads the operation intention of the arm and the vector ρ shows the direction and torque size of the arm. Through the geometric calculation, we can quickly distribute to assist the user's arm force. The results of the accurate calculation of the 2 motors can be quickly transferred to the user's arm movements. It will not interfere and will smoothly assist the user. The main results of this paper are the following:

1. The vector synthesis of the bi-axial sensing value and the vector decomposition of the motor torque can simulate and share the actions of the person under rehabilitation.
2. The rehabilitation robots, unlike industrial

robots, should maintain high accuracy and presentation. Its purpose is to assist the user to complete the physical activities during the rehabilitation process. Therefore, it can perform in a low cost budget but with high availability results.

3. Although we did not conduct any further analysis on the control responsibility of this system, the test results can meet the smoothness requirements of the users' movements.

4. To enhance the smoothness of the overall operation of the arm exoskeleton, the motor can be converted into a high-speed motor with planetary gear reducer.

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