Universal Exoskeleton Arm Design for Rehabilitation

Siam Charoenseang and Sarut Panjan
Institute of Field Robotics, King Mongkut's University of Technology Thonburi, Bangkok, Thailand
Email: siam@fibo.kmutt.ac.th, sa_panjan@hotmail.com

***Abstract*—This paper proposes the design of a 4 DOF exoskeleton robotic arm for rehabilitation. This proposed robot arm can be used easily with either the user's left or right arm. This robot arm is designed to have low inertia, high stiffness link, and zero backlash transmissions. It supports the patient's arm during rehabilitation which is a repetitive task and takes a period of time. Each joint of this exoskeleton can be rotated from -90 to 90 degrees. From the result of joint trajectory of exoskeleton, this exoskeleton can support the daily movement of human arm and can be utilized for both arms. Furthermore, this proposed robot arm can be applied as a therapeutic and diagnostics device for physiotherapy, assistive device for human power amplifications, a haptic device for virtual reality simulation, and a master-slave device for teleportation.**

***Index Terms*—exoskeleton, rehabilitation, human-robot interface**

I. Introduction

According to the data from the Stroke Center at the University Hospital, stroke is the second worldwide leading of death which is approximately 4.4 million of the total 50.5 million deaths each year [1]. In the United States, more than 4 million people survived from a stroke are disabled. Ten percents of stroke patients can be recovered almost completely but 75 percents of stroke patients will lose or have impaired motor function and 15 percents die after the stroke. Rehabilitation cost per person is approximately $140,048 [2]. Because of very expensive rehabilitation cost, most of patients are lack of opportunities for rehabilitation.

Recently, many robots have been used in rehabilitation and training tasks. In general, robotic rehabilitation can be categorized into two styles which are wearable and non-wearable. For arm rehabilitation, joints and links of the wearable rehabilitation robot are usually designed correspondingly to the patient arm such as the cable-actuated dexterous exoskeleton for neurorehabilitation (CADEN)-7 [3]. The design of "CADEN" applies the cable-pulley to transmit torque/force from motor to each joint. This design can reduce weight of exoskeleton. ARMinIII [4] is designed to have 3 degrees of freedom for shoulder and 1 degree of freedom for elbow. Robotic Upper Extremity Repetitive Trainer (RUPERT) [5] has five actuated degrees of freedom for each joint which is driven by compliant pneumatic muscle actuators (PMA). The Mechatronics and Haptic Interfaces (MAHI) [6], [7] is designed to have 5 degrees of freedom for the elbow and forearm. The wrist of this exoskeleton is a 3-RPS (revolute-prismatic-spherical) joint. The non-wearable rehabilitation robots are usually adapted from the industrial robots but only one point of physical contact between patient wrist and the robot's end-effector such as MIT-MANUS [8] and MIME [9]. Both devices are designed for rehabilitation of shoulder and elbow joints. Benefits of wearable robotic rehabilitation are controlling and generating of force feedback to each user arm's joint. Those rehabilitation robots are usually designed for right or left arm only. On the other hand, the advantage of non-wearable robot is flexibility for rehabilitation but it cannot control or generate force feedback to all joints at the same time.

All previous robotic devices for rehabilitation have mentioned limitations. Hence, this paper proposes a new design of wearable robotic exoskeleton device which can be used for right or left arm. Moreover, this proposed exoskeleton device can control and provide force feedback to each joint of user during for rehabilitation and training.

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II. Requirements

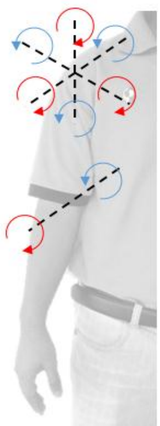

Figure 1. Degree of freedom in the upper-limb

Upper arm rehabilitation device requires movement of shoulder joint and elbow joint for both arms. The movement of the shoulder and elbow are contributed to the rotation and translation of the wrist. Shoulder is the most complex joint in the human arm i.e., movement of the shoulder joint can be estimated as rotation in single ball-and-socket joint with 3 degrees of freedom. Elbow has a hinge joint which can rotate with 1 degree of freedom as shown in Fig. 1.

Kinematics of the exoskeleton arm is relied on the human upper limb especially on arm. The human arm has 4 degrees of freedom which consist of abduction/ adduction, flexion/extension and lateral rotations/medial rotations of the shoulder and flexion/extension of the elbow. The workspace and torque capabilities of human arm can be shown in Table I. Therefore, the design of exoskeleton device should be considered correspondingly to these joint's ranges and torques.

TABLE I. WORKSPACE AND TORQUE CAPABILITIES OF ARM [6]

Joint	Workspace	Torque
Shoulder Abduction/ Adduction	134/48 °	62.5 Nm
Shoulder Flexion/ Extension	61/188 °	62.5 Nm
Shoulder Lateral/ Medial	97/34 °	62.5 Nm
Elbow Flexion/ Extension	142/0 °	36.2 Nm

III. EXOSKELETON DESIGN

In the mechanical section, the proposed robotic exoskeleton arm is designed to have 4 degrees of freedom (DOF). Joint 1, 2, and 3 represent shoulder joints and joint 4 represents elbow joint. Link 1 and link 2 are aligned with the upper limb as shown in Fig. 2. DH-parameters in Table II are used to analyze the position and orientation of wrist. Transformation matrix of upper limb exoskeleton can be calculated from the Equation 1.

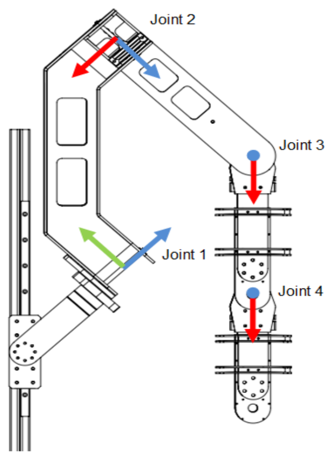

Figure 2. Configuration of robot arm axes

TABLE II. DH-PARAMETERS OF REHABILITATION ROBOT ARM

Link	α_{i-1}	a_{i-1}	d_i	θ_i
1	-45	0	0	θ_1
2	-90	0	0	θ_2
3	90	0	0	θ_3
4	0	l_3	0	θ_4

$$^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i\sin\theta_i & \sin\alpha_i\sin\theta_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\alpha_i\cos\theta_i & -\sin\alpha_i\cos\theta_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

A cable-driven actuating system is used to transmit force and torque to each joint of rehabilitation robot arm. Therefore, this design can reduce the robot arm’s weight since the servo motors are not mounted on the robot arm. Furthermore, this robot arm is designed to be used with the left arm or right arm by rotating joint 2 about 180 degrees as shown in Fig. 3.

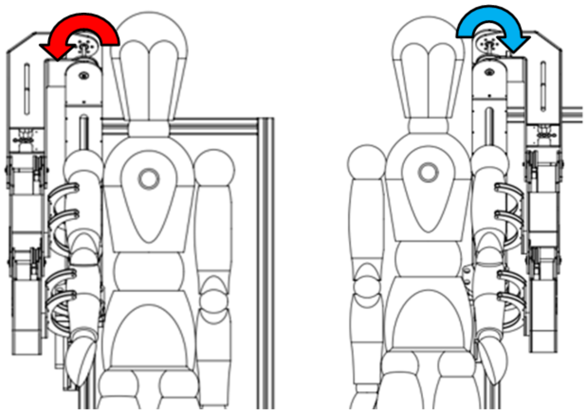

Figure 3. Configuration of robot used for right and left arm

A cable-driven actuating system consists of two pulleys and bowden cable. Pulley 1 is a driving pulley and pulley 2 is a driven pulley. The pulley 2 is mounted at each joint. It can be rotated freely around that axis and force/torque sensed by load cell will transfer from the pulley to that joint. In the propose design, four force sensors are attached on the rehabilitation robot arm at each joint. Each force sensor can sense the external force exerted on each joint in clockwise and counterclockwise directions. The structure of force sensor mounted on each joint can be shown in Fig. 4.

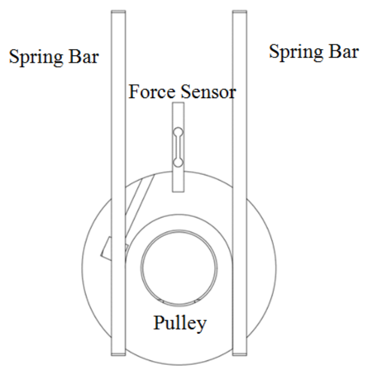

Figure 4. Structure of force sensor mounted on each joint

The supporting section consists of two parts which are forearm mount and robot supporting frame. Forearm support is designed for the left or right arm. The robot supporting frame is shown in Fig. 5. The design of forearm support is shown in Fig. 6. This support utilizes the magnet to be attached and reattached with the main frame easily as shown in Fig. 7.

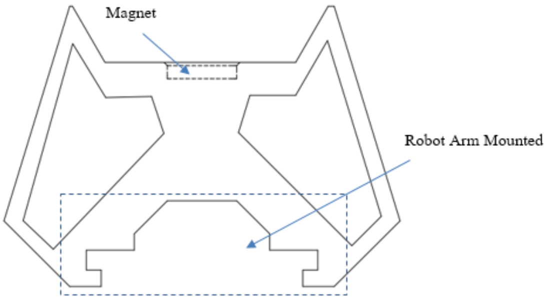

Figure 5. Forearm support

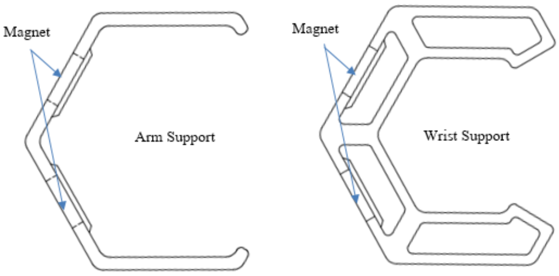

Figure 6. Robot supporting frame

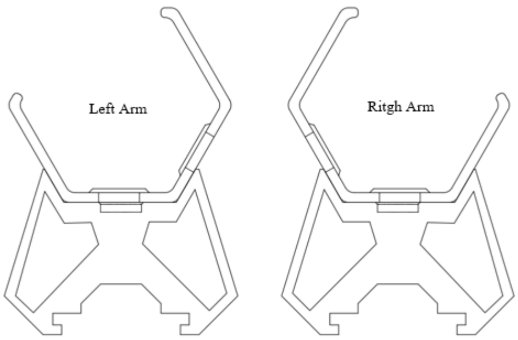

Figure 7. Mechanical design of arm support

In the electrical and electronics section, AC servo motors are used for actuating the upper limb exoskeleton. Four-axis motion controller, NI PCI-7356, is used to control all motors at the same time. Force sensors are used to detect the physical forces which act on each joint of upper limb exoskeleton. Output from the force sensor has very low voltage so amplifier is used to magnify the signal from 10 µV to 10V as shown in Fig. 8. Amplifier is mounted closely to each joint for reducing noise from the signal cable. Then, the signal from amplifier will be sent to the main computer via DAQ card, NI USB-6210, as shown in Fig. 9.

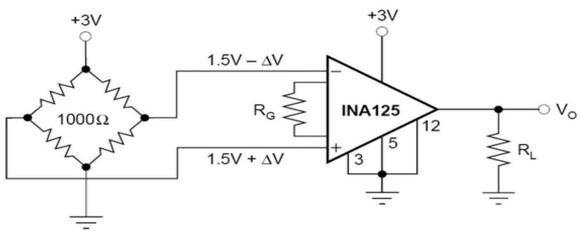

Figure 8. Force sensor amplifier circuit

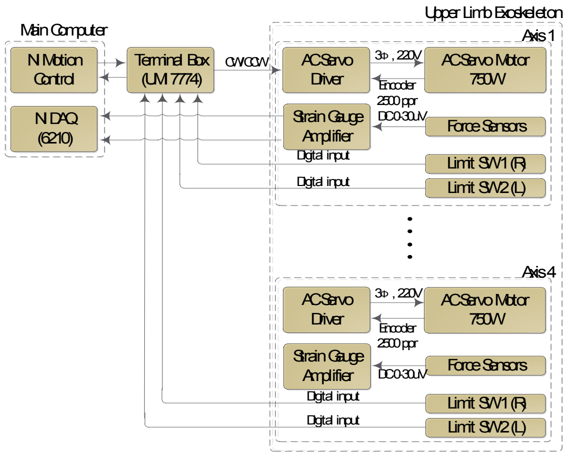

Figure 9. Robotic exoskeleton system components

IV. IMPLEMENTATION

Exoskeleton arm can be used with the left or right arm by rotating the joint 2 about 180 degrees and flipping the forearm support for swapping between arms as shown in Fig. 10. Force sensor is mounted on each joint of exoskeleton in order to detect forces which act on each joint of exoskeleton in the clockwise and counterclockwise direction. Four AC servo motors in exoskeleton are used to generate forces/torques and transfer those forces/torques to the exoskeleton joint via Bowden cables.

Figure 10. Robotic exoskeleton configuration

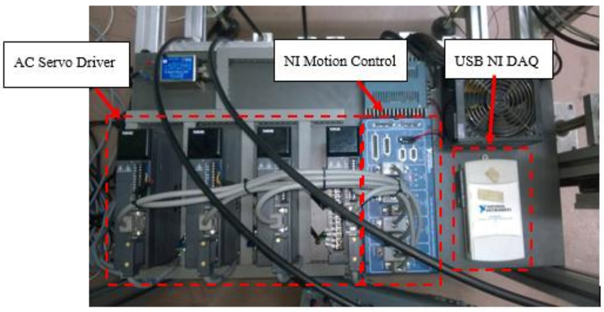

Figure 11. Exoskeleton controller

In this exoskeleton arm system, the controller module, NI-motion controller, is used for receiving position and velocity command from the main computer and controlling all AC servo motors. It can communicate with each motor using CW-CCW pulse via AC servo driver as shown in Fig. 11. The force receiving module, NI USB DAQ device, is used for receiving force signal from the force sensor via the force amplifier module. Force amplifier module as shown in Fig. 12 are mounted on each joint of exoskeleton.

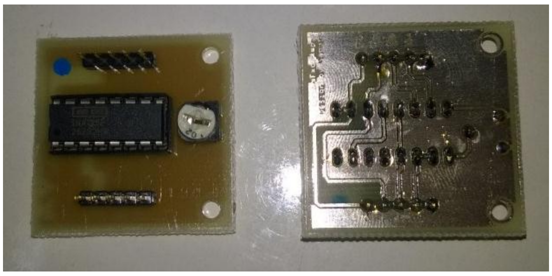

Figure 12. Force amplifier module

V. RESULTS AND DISCUSSION

From the statistical distribution of human arm joint angles and capabilities of arm as shown in Table I, the proposed exoskeleton arm is designed to have 4 degrees of freedom. There are 3 degrees of freedom at the shoulder and 1 degree of freedom at the elbow. Each joint of exoskeleton motion can be rotated from -90 to 90 degrees. AC servo motor consumes about 750W with gearbox ratio of 50: 1. It is used to generate force/ torque to each joint via bowden cable. Maximum force at each joint of exoskeleton is more than 120 Nm. which can cover all motions of human arm as shown in Fig. 13-Fig. 16.

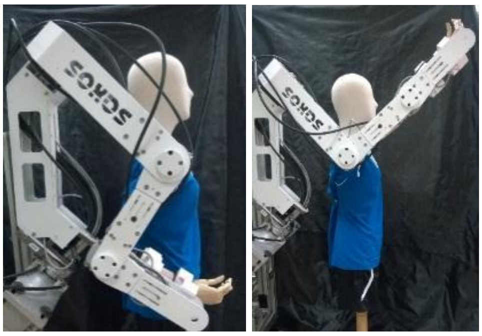

Figure 13. Shoulder joint flexion-extension

Figure 14. Shoulder abduction.

Figure 15. Shoulder joint internal-external rotation

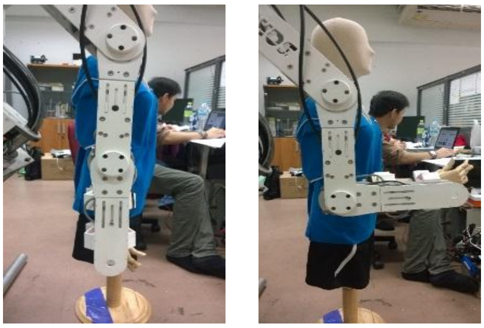

Figure 16. Elbow joint flexion-extension

For safety purpose, all initial experiments in this research were conducted with the human model instead of real human. In this exoskeleton system, there are three types of gestures to be trained and tested. First gesture is to move the user's arm, human model's arm in this case, from right to left for the right arm configuration or from left to right for the left arm configuration as shown in Fig. 17. Second gesture is to move the model's right or left arms from the lower to upper position as shown in Fig. 18. Third gesture is to move right arm from the lower right position to the upper left position or move the left arm from the lower left position to the upper right position as shown in Fig. 19.

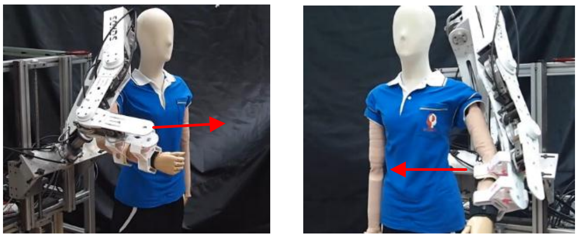

Figure 17. Gesture 1: X-axis movement

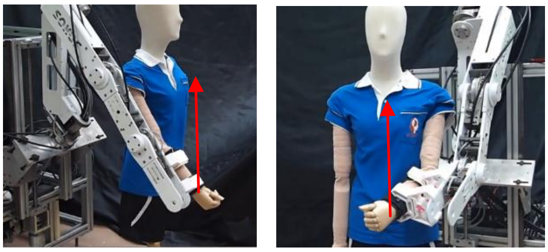

Figure 18. Gesture 2: Z-axis movement

Figure 19. Gesture 3: Diagonal movement

After three sets of experiments were conducted, the joint's angles and velocity trajectories of three gestures can be plotted. The right arm's trajectories are shown in Fig. 20-Fig. 25. All trajectories were predefined and replayed to control the human model to move accordingly to those predefined paths. The controller can take care of arm's load and guide the arm from the starting point to the destination for both arms successfully.

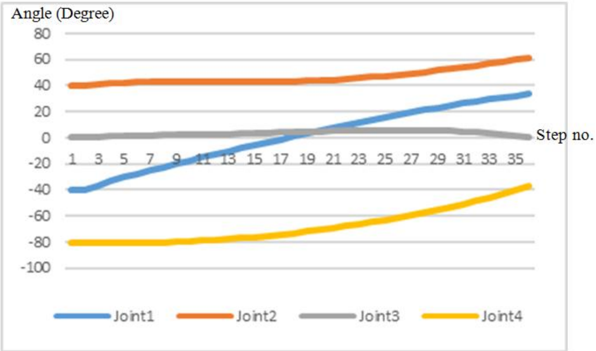

Figure 20. Gesture 1: Joint's angle trajectory.

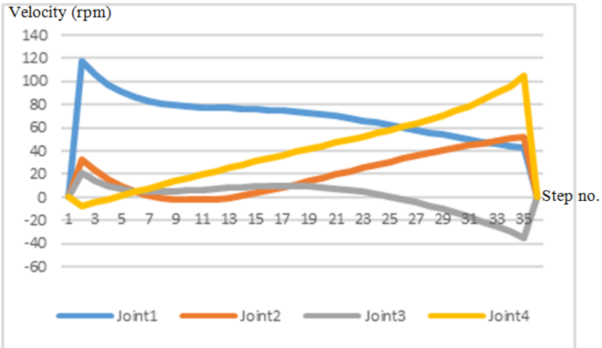

Figure 21. Gesture 1: Joint's velocity trajectory

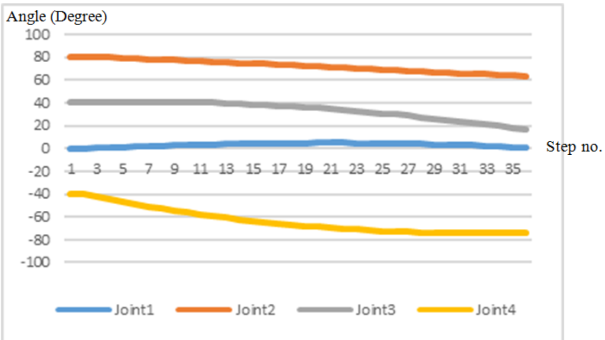

Figure 22. Gesture 2: Joint's angle trajectory.

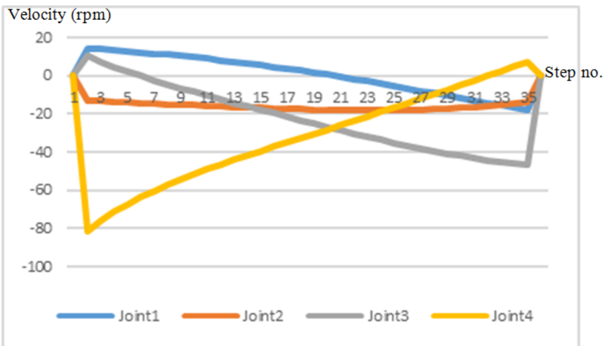

Figure 23. Gesture 2: Joint's velocity trajectory

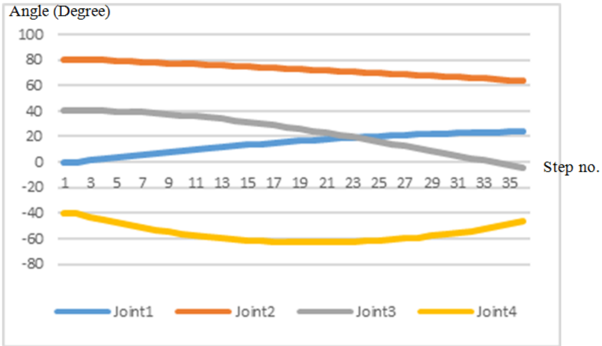

Figure 24. Gesture 3: Joint's angle trajectory

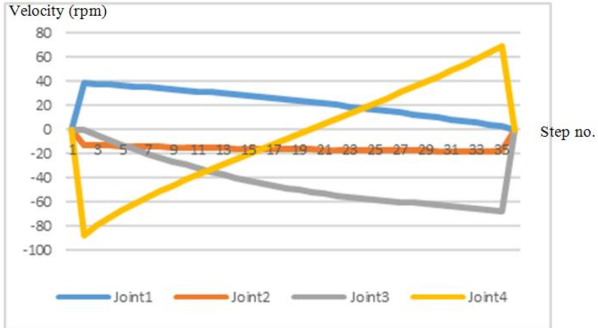

Figure 25. Gesture 3: Joint's velocity trajectory

In the first gesture, exoskeleton moves the user arm along the x-axis. Joint 1 is rotated from -40 to 38 degrees, joint 2 is rotated from 40 to 60 degrees, joint 3 is rotated a little bit, and joint 4 is rotated from -80 to -38 degrees. For the second gesture, exoskeleton moves the user arm along z-axis. Joint 1 does not rotate, joint 2 is rotated from 80 to 60 degrees, joint 3 is rotated from 40 to 20 degrees, and joint 4 is rotate from -40 to -58 degree. In the last gesture, exoskeleton moves the user arm diagonally. Joint 1 is rotated from 0 to 22 degrees, joint 2 is rotated from 81 to 62 degrees, joint 3 is rotated from 40 to -5 degrees, and joint 4 is rotated from -40 to -62 degrees.

VI. Conclusions

The 4-DOF robotic exoskeleton arm was designed and built at the Institute of Field Robotics, King Mongkut's University of Technology Thonburi. The key object of this research is to reduce work load of physiotherapist. Therefore, this robot arm can rotate cover the range of -90 to 90 degrees for each joint. Hence, it covers the range of human joint's motion. The arm can be configured by rotating joint 2 to 180 degrees for the use of right or left arm. This exoskeleton arm can be utilized for rehabilitation and training purposes. The forward kinematics, inverse kinematics and trajectory planning of this device are created based on the Denavit-Hartenberg's parameter model. Force sensor and force amplifier modules are mounted on exoskeleton joints. They are used to receive physical forces from the user for controlling the motion of exoskeleton.

From experimental results, the trajectory of exoskeleton arm illustrated the joint's positions and joint’s velocity. Motion of exoskeleton can move smoothly in its workspace with the model’s arm. Maximum joint’s velocity of exoskeleton arm is about 120 rpm. Moreover, there levels of safety were implemented. For mechanical safety, the arm was designed to be moved within the range of -90 to 90 degrees. For electrical safety, the large emergency switch was added to stop all servo motors’ motions if it is pressed. For software safety, limited joint’s angle command was implemented.

Future works of this research will focus on force control algorithm for controlling motion of exoskeleton joints smoothly corresponding with the motion of human arm joints.

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Siam Charoenseang, Ph.D. received Master and Ph.D. degrees in electrical and computer engineering from Vanderbilt University, USA in 1995 and 1999. In 1992, He received Bachelor degree in applied physics from King Mongkut’s Institute of Technology Ladkrabang, Thailand. He was a member of the development and localization team of one laptop per child project at MIT, Cambridge, USA, 2006. Since 2002, he has been a leader in several researches that are funded from the National Research Council of Thailand. At present, he is an associate professor and director of Robotics and Automation program at the Institute of Field Robotics, King Mongkut’s University of Technology Thonburi, Thailand. His research interests include Human-Computer Interface, Virtual Reality, Intelligent Robotics, Telepresence, and Mechatronics.
Assoc. Prof. Dr. Siam Charoenseang received Thai Government Scholarship during 1993-1999. He was a committee member of IEEE International Conference on Industrial Technology, Bangkok, Thailand, Dec, 11-14, 2002. He is currently an executive member of Thai Robotics Society.

Sarut Panjan received Bachelor of Science in Technical Education Program in Electrical Engineering from King Mongkut's University of Technology North Bangkok, Thailand in 2008. , he received Master degree in robotics and automation engineering from King Mongkut’s University of Technology Thonburi, Thailand. She is currently a Ph.D. student of robotics and automation program at the Institute of Field Robotics, King Mongkut’s University of Technology, Thonburi, Thailand. He is teacher at the Faculty of Technical Education, King Mongkut's University of Technology North Bangkok, Thailand. He research interests are Human-Robot Interaction, Augmented Reality, Virtual Reality and Control System. He colleagues received the best technique award in Thailand Robot at Home Championship, 2011. He received full scholarship in Master of Engineering Program in Robotics and Automation from National Science and Technology Development Agency, 2009-2011.

