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Archives of Orthopaedics Research Article

Performance Validation of An Upper Limb Exoskeleton Using Joint ROM Signal

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Abstract

Exoskeleton systems are emerging for robotic assistive surgery and rehabilitation of neurologically impaired patients. A novel upper extremity (UE) exoskeleton has been developed in our lab, potentially to be used for robotic assistive surgery and stroke rehabilitation in our laboratory. The purpose of this study was to introduce the methodology of voluntary control of the UE exoskeleton by processing the range of motion (ROM) of UE joints. Ipsilateral-to-ipsilateral synchronous (IIS) control and ipsilateral-to-contralateral mirror (ICM) control mechanism were designed for UE exoskeleton movement control. A 3D simulation was performed to validate mechanical designs for kinesiologic motion. The performance of the ROM-controlled UE exoskeleton was then validated among six healthy subjects. The UE exoskeleton performed drawing movements in a 2D panel. The drawings created by the UE exoskeleton were compared to the drawings created by a healthy subject to determine the accuracy of the drawing performance. Reliability statistical analysis (Cronbach test) was performed to determine the inter-rater agreement between subject performance and UE exoskeleton performance. Results showed an excellent agreement between the human drawings and exoskeleton drawings (Cronbach Alpha value = 0.904, $p<0.01$). This study demonstrated that ROM of UE joints can be processed for voluntary control of a UE exoskeleton. Potentially, UE exoskeletons can be used for robotic assistive orthopaedic surgery and UE rehabilitation trainings.

Keywords: Exoskeleton, Upper extremity, Voluntary control, Range of motion

Introduction

Upper extremity (UE) exoskeletons were developed for industrial applications where assistive force enhancement was needed, but there have also been developments for use in telemanipulation and virtual reality, clinical applications such as assistance in orthopedic surgery, and orthopedic rehabilitation [1,2]. Clinical applications include rehabilitation therapy for limbs and robot assisted orthopedic surgery, such as positioning tasks where high accuracy is needed for bone resection or alignment of an implant within a bone [3,4]. Uses of exoskeletons in rehabilitation include therapy after orthopedic surgery, stroke survivors, and other brain injury survivors with one brain hemisphere damaged [5,6]. The above examples show uses of the exoskeleton for operator assistance, they can also be used in a novel rehabilitation approach in which the UE exoskeleton is used both to assist the patient in transferring motion from one place to another, namely from one arm to the other, but also to assist in actual rehabilitation of the affected arm. Such an approach makes use of a mirroring pattern between the two arms and is particularly effective for survivors of brain damage or for learning to effectively use a prosthetic limb.

Rehabilitation of limbs affected by hemiparesis must include consideration for routine tasks that are typically performed daily. Such tasks might involve synchronous or asynchronous movements; asynchronous movements could be bilateral or unilateral [7]. Bilateral training is effective and involved in central nervous system (CNS) neuroplasticity. When movement is made with one limb, the CNS activity that initiates that movement affects the part of the CNS associated with the opposite limb [5]. Additionally, brain activity involved in the bilateral arm and hand movements is not merely composed of the summation of the mechanisms of unilateral movements; specific neural control mechanisms that fire only during bimanual movements are engaged in the supplemental motor cortex (SMA) and the primary motor cortex (M1) [8]. Making use of this concept is known as motor control training. It has long been known in the field of physiotherapy that training with bimanual movements is beneficial for patients with hemiparesis. It is worth noting that unilateral practice with the unaffected limb can be effective in treating the affected limb, and for this reason, this practice may be bilateral.

Voluntary control of an upper arm exoskeleton involves synchronous movements between the user and a robot at user's will. Researchers have developed newer upper limb exoskeletons with promising outcomes for obtaining better control accuracy for desired tasks. Several exoskeletons with multiple degrees of freedom (DoF) of the human arm have been developed, including the X-Arm 2 [9], MGA Exoskeleton [10], ARMin [11], and VI-Bot [12]. However, the requirements for an assistive robotic system for medical use are different from industrial applications. A specialized approach in designing an exoskeleton for rapid and precise positioning tasks is required. Current limitations include range of motion, alignment, bulkiness, weight, and cost.

This paper presents a novel robot control mechanism, which is named the mirror or synchronous motion control strategy, along with strategies for fostering robotic systems in clinical use. Ranges of motion (ROM) of multiple upper arm joints are encoded and then decoded for the upper arm exoskeleton movement control. The objective of the study was to determine the effectiveness of processing ROM signals for exoskeleton control by evaluating the performance of an exoskeleton based on operation accuracy and precision of movements. The accuracy of the system performance was tested and validated among healthy volunteers.

Materials and Methods

Mechanical design

Our upper arm system exoskeleton has four joints to provide multiple degree of freedom (DoF) motions for the exoskeleton (Figure 1). Synchronous or mirror control technique was used for precise movement control. A bilateral UE exoskeleton system was developed for this study. The joints of one exoskeleton arm were installed with angular decoders to detect the angles of the joints during motion. The obtained angular information was processed and encoded by a computer to control the movements of ipsilateral or contralateral exoskeleton movements. This ipsilateral-for-contralateral mirror (ICM) control technique was designed for stroke patients or orthopaedic postoperative rehabilitation training, which uses healthy arm joint motion information for affected arm motion control. While ipsilateral-to-ipsilateral synchronous (IIS) control technique can potentially be used for surgical robot movement control by surgeons.

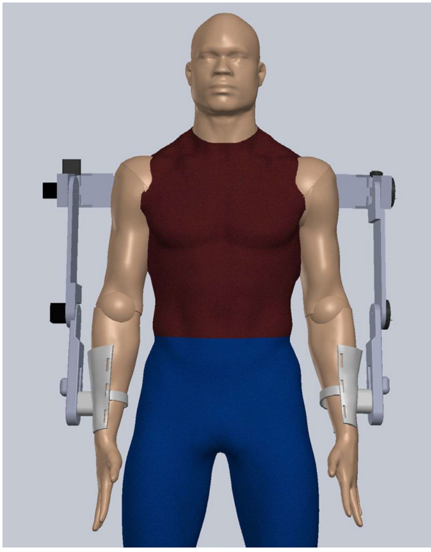

Figure 1: Exoskeleton 3D Design.

The exoskeleton for the affected arm has motors in addition to the encoders. User-initiated movements detected from the healthy arm were transferred to the exoskeleton for the affected arm motion control, resulting in a synchronous movement of UE exoskeleton and healthy subject arms. The encoders on the exoskeleton for the affected arm provided feedback on the angles to validate that the angles between the two exoskeletons match.

There were four-DoF motions of each arm exoskeleton. Each DoF of motion was controlled by a stepper motor (Figures 1 and 2). Three stepper motors were used by shoulder glenohumeral (GH) joint motion along horizontal (X), vertical (Y), and sagittal (Z) directions. The elbow joint of the UE exoskeleton was designed with one DoF of motion for flexion and extension. The motion of exoskeleton shoulder joint at the Z axis was controlled by Motor 1, which provides an actuation for adduction

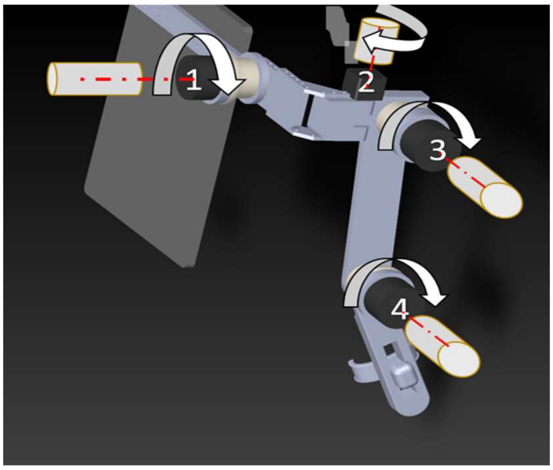

Figure 2: Shows the UE exoskeleton with multiple DoF motions actuated by 4 stepper motors.

and abduction of the shoulder joint. Motor 2 provided actuation for humerus internal and external rotations at the Y axis. Motor 3 flexed and extended the exoskeleton shoulder joint at the X axis. Motor 4 flexed and extended the elbow joint of the UE exoskeleton (Figure 2).

Joint movement

Our UE exoskeleton is intended to assist in human upper limb movements. There is a need for the axes of the exoskeleton to be perfectly aligned to the human joint axes [13]. There is a misalignment between the joints of the exoskeleton and those of the human which can cause the generation of unwanted interaction forces and mispositioning. To address this issue, the proposed exoskeleton structure was designed to keep the shoulder and elbow joints aligned. Axis of motors 1, 2, and 3 (Figure 2) was aligned and met with the shoulder rotation center of rotation. The axis of motor 4 was aligned with the elbow joint flexion/extension axis. The length of forearm of the exoskeleton was adjustable during the motion thus avoiding the misalignment between the exoskeleton and user.

Control system

There are several actuation technologies reported previously [14], in our study, each joint of the exoskeleton for the affected arm was installed a DC motor with a planetary gearbox having a gear ratio such as 263:1. Position measurements were obtained using an encoder for closed-loop feedback of position information. This type of encoder had high-resolution (600 pulses per revolution) with guaranteed high precision and a response frequency of 20KHz (a period of 50 μs). Each motor is controlled by a separate microprocessor (ARDUINO MEGA 2560 REV3, with a 16 MHz, 0.06 μs clock speed) and motor speed 0.13sec/60 degree at 8.4V (Figure 3).

System validation and performance

Three dimensional (3D) simulations were used to determine any dynamic problems for different joint movements and to make necessary changes to mechanical designs in simulations. Simulations were performed before the final mechanical design was set-up for the prototype and human subject testing. The simulations

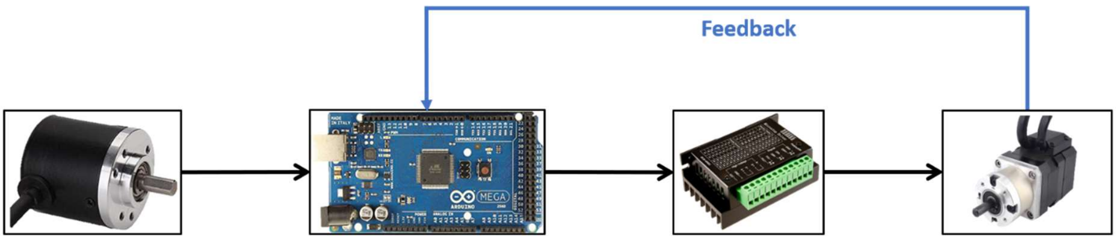

Figure 3: Single joint control mechanism showing the flowchart of ROM signal processing for motor control.

were done in SOLIDWORKS software using 3D human models with moving joints to mimic the range of motion in shoulder and elbow joints. The segments of the model were established based on lengths from the average male size. The software monitored whether the design could be used to perform the full range of motion in the workspace.

System validation and performance

(1) Subject Requirement. This study was performed in the Robotic Rehabilitation Lab, six healthy subjects were recruited in study. They had no evidence or known history of skeletal or neurological disorders and displayed a normal range of motion and muscle upper-limb strength. The study has been approved by the ethics committee (Institutional Review Board) of Wayne State University.

(2) Study objectives and design. The exoskeleton mounted with ROM signal decoders was placed on the arm of the dominant hand. The robot arm was placed in a parallel position with the subject. The subject repeatedly drew a pattern, and the motorized exoskeleton performed the same motion pattern (Figure 4). The results were analyzed by tallying the distances between expected and actual locations drawn with motorized assistance.

The drawing was performed on a vertical plane. The pattern was a square-shape to allow for four different movements [15]. The panel had four corners, each of which was 15 cm from the other point. The shoulder centers of rotation of both the subject and the robot arm were aligned with the centers of the square shapes. There was a pen affixed to the hand of the subject and another to the robot arm. The subject proceeded to draw from Corner 1 to each of the four targets, which included the movements from Corner 1 to 2, 2 to 3, and 3 to 4. The subject drew from one target to the next until all four targets had been reached (1, 2, 3, 4). The test was repeated three times (Figure 5).

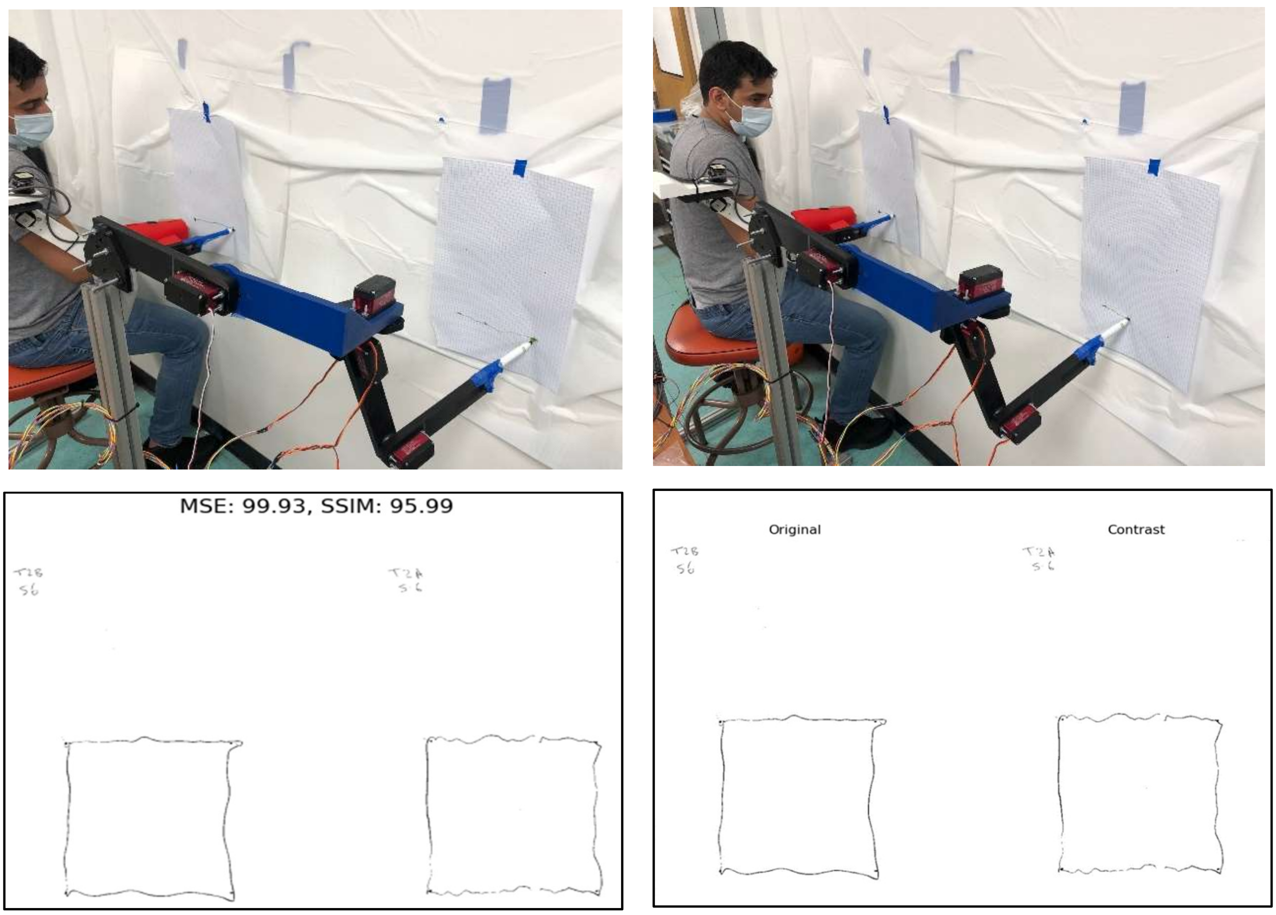

Figure 4: One subject performed two trails. The results were then compared using CA, MSE and SSIM methods.

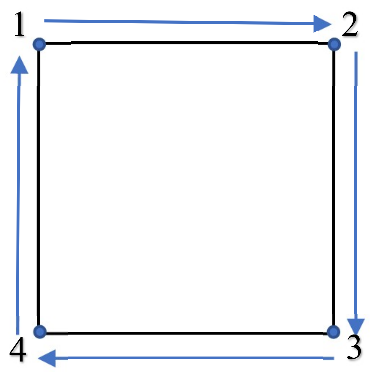

Figure 5: The direction of drawing a square route.

The template for the square shape was on graph paper. Figure 4 shows the direction of drawing movements. With the healthy arm, the subject drew from Corner 1 to Corner 2, and then made an angle to draw from Corner 2 to Corner 3. The associated drawing done by the robot arm was used for comparison. The images were processed using Python toolboxes (version 3.9.1) to define the percentage of the match. Repeated measures were used to compare the percentages of matching points. Both X and Y for each corner was compared to each x and y of the original drawing.

Mean squared error (MSE) and structural similarity index (SSIM) were used to measure the difference of position points on the drawings between human and robot. SSIM is specifically used to quantify differences between similar images. It was used in this study to incrementally compare small segments (boxes containing both x and y information) of the two images, with increments going in both the x and y directions. The resulting index is the mean value for the entire image.

Statistical analysis

Reliability test (Cronbach test) was used to determine the agreement between human and robot drawings. Cronbach's Alpha was measured to determine the extent of inter-rater agreement between human and robot drawings. Statistical software SPSS (version 26, IBM, Armonk, NY) was used for statistical analysis with p value smaller than 0.05 considered to be significant.

Results

Validation of mechanical design

A 4-DOF exoskeleton to support activities of daily living ADL was reproduced (Figure 6) to determine the efficiency of processing joint ROM information for robot motion control. The exoskeleton enabled the shoulder and the elbow 3-DoF and 1-DoF of movement respectively, allowing the UE exoskeleton to accomplish a large range of motion by the wearer.

Figure 6: 3D-printed 4-DOF Bilateral Upper-limb Exoskeleton.

Range motion of UE exoskeleton

The UE exoskeleton moved within a 3D coordinate system obtaining the full range of motion as it was designed, enabling the user to perform daily activities of life. The outcome of ROM for the exoskeleton workplace is shown in Figure 7 and Table 1.

For the three methods used to validate the performance of the exoskeleton system: The Cronbach's Alpha result was 0.996 (reliability Cronbach test, $p<0.01$), MSE showed the average match between two images as 0.998 similar (reliability Cronbach test, $p<0.01$), and the SSIM average between the two images is 0.904 (reliability Cronbach test, $p<0.01$), suggestive of 90.4%-99.6% of matching (Table 2).

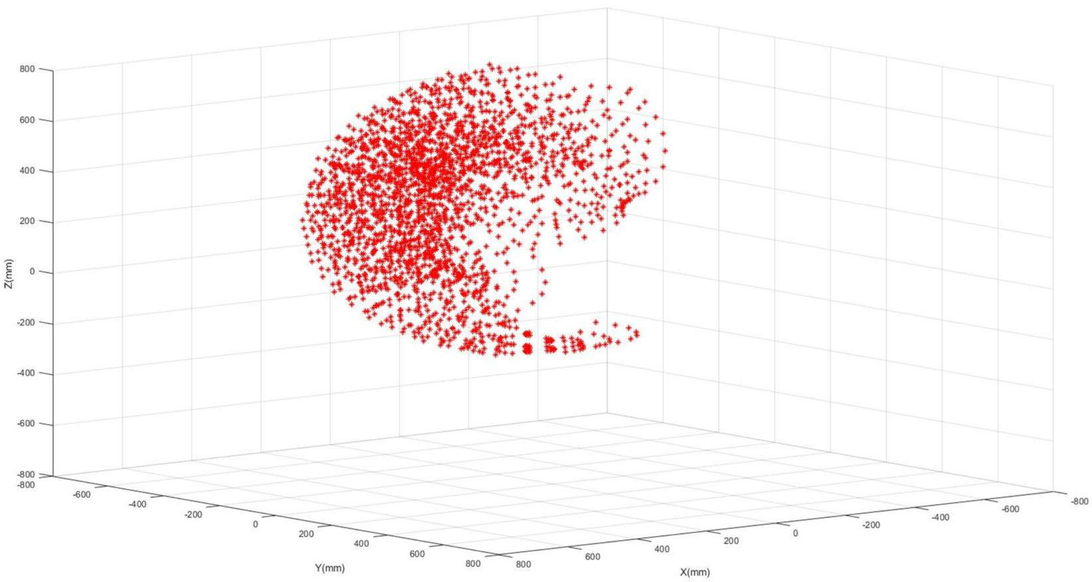

Figure 7: Exoskeleton workplace in 3D space.

Joint Number	Joint 1(shoulder) Abduction/Adduction	Joint 2(shoulder) Flexion/Extension	Joint 3(shoulder) Internal/External Rotation	Joint 4(Elbow) Flexion/Extension
Range of Degree of Freedom (DOF)	(0°) – (130°)	(-60°) – (80°)	(-30 °) – (120°)	(0°) – (140°)
**The zero position is standing up without moving upper limb, + direction toward body center, - direction away from body center				

Table 1: Measured Outcomes of Range of Motion.

Structural similarity index (SSIM)	**Mean squared error (MSE)**	**Trail Number**	**Subject**
80.24	99.83	1	1
83.48	99.80	2	
85.54	99.72	3	
96.46	99.70	1	2
91.76	99.29	2	
72.55	99.30	3	

94.67	99.94	1	3
95.71	99.96	2	
96.15	99.91	3	
93.82	99.94	1	4
93.28	99.93	2	
95.31	99.73	3	
91.92	99.92	1	5
86.58	99.90	2	
95.11	99.93	3	
95.31	99.95	1	6
85.85	99.89	2	
95.11	99.93	3	
90.49166667	99.80944444	Average	

Table 2: Drawing comparison results of MSE and SSIM Measures.

Discussion

In this paper, it is demonstrated that ROM signal of a subject's upper limb joints can be processed to precisely control a wearable exoskeleton system. Potentially, it can be used for the voluntary control of a rehabilitative exoskeleton or robotic assistive robots. This novel approach generated a mechanism for using a robotic device with IIS or ICM control algorithms for UE exoskeleton movement control.

Volitional-control robotic assistive rehabilitation improved patient treatment outcomes [16-18]. Most of these studies used brain wave (electroencephalography, EEG) or electromyography (EMG) signals for voluntary control of exoskeletons or end effectors [16]. In this study, ROM of UE joint was used for voluntary control of an UE exoskeleton. This ipsilateral-to-contralateral mirror (ICM) control mechanism used the healthy arm ROM signals to control the affected arm exoskeleton for motion assistance. Potential benefits of the bilateral exoskeleton system include growing independence for patients. The device provides repeated and intensive physiotherapy sessions, thus reducing both the therapist's burden and healthcare expense. Progress can be chart-recorded with ROM information output from the angular decoder. In terms of orthopaedic applications, this device provides measurements of many limb movements for kinematic and dynamic parameters, thus providing performance-related metrics and healing progress record charts. In our research, the ICM controlled exoskeleton was designed to be used for rehabilitation training, the IIS (ipsilateral-to-ipsilateral synchronous) control mechanism was designed to provide a control mechanism for a remote surgical robot. A surgeon may wear a ROM-control exoskeleton to guide a remote robot to perform a surgery. Our study demonstrated that the IIS control mechanism accurately read the ROM of joints and synchronously control the movement of a robot.

Research of human machine interface (HMI) is a hot topic recently. However, processing human motion intents for robot control still has significant challenges and is open for further research [19]. Consequently, optimization and selection of the best control method is a difficult task. The control methods for upper-limb exoskeleton robots are classified in several ways. They can be classified based on the types of input information, output information, or architecture of the controller [18]. The classification based on controller input signals is the most important issue, as the input signals are critical to identifying the human motion. Control methods based on controller input are categorized based on the input signals from biological measurements, non-biological measurements, or platform-independent sources. Control methods based on biological signals can be obtained directly from a human, including electromyography (EMG) and electroencephalography (EEG) signals. Techniques have been developed to receive and interpret information regarding user intention from non-biological signals as input to the control methods [20]. These control methods identify human motion by using instrumentation to sense the results of biological activity rather than the biological activity itself. Some examples of such instrumentations are torque/force sensors or dynamic modeling of the human limb. In platform-independent control methods, various control strategies are used with the exoskeleton developments. These control strategies are implemented to improve the features and performance of the control systems in exoskeleton robots, but they make the systems complicated and large [21-23]. Force sensors make the whole system both expensive and bulky. The ROM signals for UE exoskeleton control in this study demonstrated that it is a reliable method for medical robot control.

Current available bilateral upper-limb exoskeletons have limited ranges of motion and are of little assistance to the affected limb of the user. Such UE exoskeletons include Bi-Manu-Track, Nudelholz, Tailwind, Reha-Slide Duo, and The Rocker for APBT, Braccio di Ferro, and Batrac [7, 13, 24, 25]. The control mechanisms of that exoskeleton are not voluntary at user's will. Our bilateral exoskeleton uses encoders to read joint angles from the healthy side and mirror those angles to the effected side. The encoder has high-resolution (600 pulses per revolution) with guaranteed high precision, and the response frequency is up to 20KHz (a period of 50 µs). Each motor is controlled by a separate microprocessor (ARDUINO MEGA 2560 REV3, which has a 16 MHz, 0.06 µs, clock speed) and motor speed 0.13sec/60 degree at 8.4V (Figure 8).

Our results indicated that the encoders read user's joint angles accurately for UE exoskeleton motion control. Comparison of the accuracy of drawings was used for system's performance evaluation. The results showed a good matching of drawing figures between human and robotic UE exoskeleton. This study demonstrated that decoding ROM signals for IIS or ICM control can be a feasible approach for research and product development of medical robots for navigation surgery or rehabilitation. It may potentially be used for chart-record of healing progress according to the digital output from the angular decoders.

Limitations of this study include that only healthy subjects were studied for our current prototype development. Future studies include a clinical study using ROM-controlled UE exoskeleton for orthopaedic post-operative UE rehabilitation and stroke rehabilitation trainings. Robot assistive surgery and robotic rehabilitation in stroke and post-orthopaedic surgery are emerging and pioneering research topics in orthopedics, more studies are required for further product development research.

Conclusion

In this paper, a novel four-DoF upper-limb exoskeleton was presented together with its motion control mechanisms. ROM signal of joints can be processed for the motion control of paired UE exoskeleton system either for the ipsilateral or contralateral arm. The ROM controlled paired UE exoskeletons can potentially be used for clinical rehabilitation or navigation of a remote surgical robot.

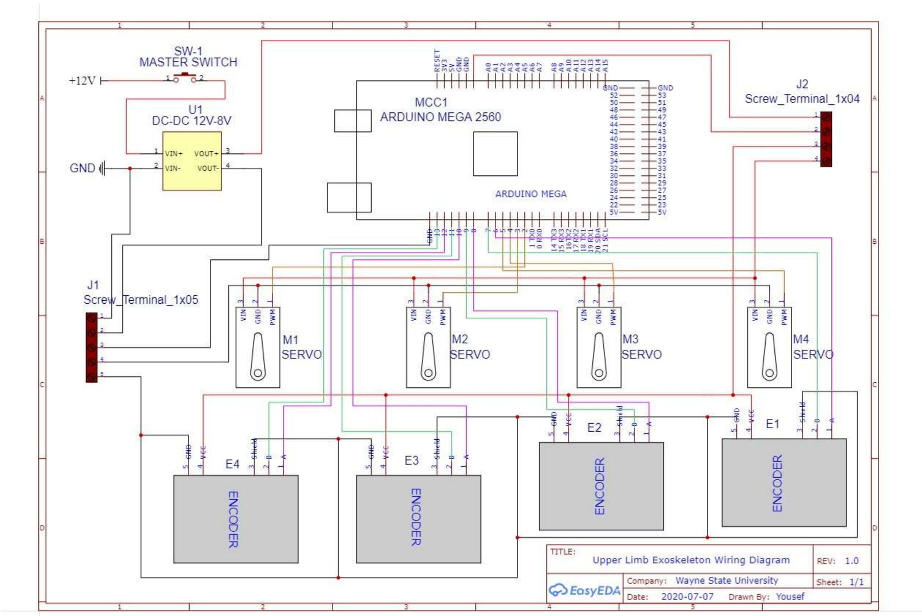

Figure 8: Diagram of the control system.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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References

1. Gopura RA, Kiguchi K. Mechanical designs of active upper-limb exoskeleton robots: State-of-the-art and design difficulties. In2009 IEEE International Conference on Rehabilitation Robotics 2009 Jun 23 (pp. 178-187). IEEE.

2. Maciejasz P, Eschweiler J, Gerlach-Hahn K, Jansen-Troy A, Leonhardt S. A survey on robotic devices for upper limb rehabilitation. Journal of Neuroengineering and Rehabilitation. 2014 Dec;11(1):1-29.

3. Hessinger M, Müller R, Werthschützky R, Pott PP. Tool position control of an upper limb exoskeleton for robot-assisted surgery. IFAC-PapersOnLine. 2015 Jan 1;48(20):195-200.

4. Lang JE, Mannava S, Floyd AJ, Goddard MS, Smith BP, Mofidi A, et al. Robotic systems in orthopaedic surgery. The Journal of Bone and Joint Surgery. British volume. 2011 Oct;93(10):1296-9.

5. Whitall J, Waller SM, Silver KH, Macko RF. Repetitive bilateral arm training with rhythmic auditory cueing improves motor function in chronic hemiparetic stroke. Stroke. 2000 Oct;31(10):2390-5.

6. Coupar F, Pollock A, Van Wijck F, Morris J, Langhorne P. Simultaneous bilateral training for improving arm function after stroke. Cochrane Database of Systematic Reviews. 2010(4).

7. Dietz V. Do human bipeds use quadrupedal coordination?. Trends in Neurosciences. 2002 Sep 1;25(9):462-7.

8. Donchin O, Gribova A, Steinberg O, Bergman H, Vaadia E. Primary motor cortex is involved in bimanual coordination. Nature. 1998 Sep;395(6699):274-8.

9. Schiele A, Hirzinger G. A new generation of ergonomic exoskeletons-the high-performance x-arm-2 for space robotics telepresence. In2011 IEEE/RSJ International Conference on Intelligent Robots and Systems 2011 Sep 25 (pp. 2158-2165). IEEE.

10. Carignan C, Tang J, Roderick S. Development of an exoskeleton haptic interface for virtual task training. In2009 IEEE/RSJ International Conference on Intelligent Robots and Systems 2009 Oct 10 (pp. 3697-3702). IEEE.

11. Nef T, Riener R. ARMin-design of a novel arm rehabilitation robot. In9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005. 2005 Jun 28 (pp. 57-60). IEEE.

12. Mallwitz M, Benitez LV, Bongardt B, Will N. C PIOUBE.

13. Ericson A, Arndt A, Stark A, Wretenberg P, Lundberg A. Variation in the position and orientation of the elbow flexion axis. The Journal of Bone and Joint Surgery. British Volume. 2003 May;85(4):538-44.

14. Letier P, Avraam M, Horodinca M, Schiele A, Preumont A. Survey of actuation technologies for body-grounded exoskeletons. InProc. Eurohaptics 2006 Conference 2006 Jul (pp. 497-500).

15. Nordin N, Xie SQ, Wünsche B. Assessment of movement quality in robot-assisted upper limb rehabilitation after stroke: a review. Journal of Neuroengineering and Rehabilitation. 2014 Dec;11(1):1-23.

16. Baniqued PD, Stanyer EC, Awais M, Alazmani A, Jackson AE, Mon-Williams MA, et al. Brain–computer interface robotics for hand rehabilitation after stroke: a systematic review. Journal of NeuroEngineering and Rehabilitation. 2021 Dec;18(1):1-25.

17. Bundy DT, Souders L, Baranyai K, Leonard L, Schalk G, Coker R, Moran DW, Huskey T, Leuthardt EC. Contralesional brain–computer interface control of a powered exoskeleton for motor recovery in chronic stroke survivors. Stroke. 2017 Jul;48(7):1908-15.

18. Gopura RA, Bandara DS, Gunasekara JM, Jayawardane TS. Recent trends in EMG-Based control methods for assistive robots. Electrodiagnosis in New Frontiers of Clinical Research. 2013 May 22:237-68.

19. Pons JL. Wearable robots: biomechatronic exoskeletons. John Wiley & Sons; 2008 Apr 15.

20. Yu W, Rosen J. A novel linear PID controller for an upper limb exoskeleton. In49th IEEE Conference on Decision and Control (CDC) 2010 Dec 15 (pp. 3548-3553). IEEE.

21. Ugurlu B, Nishimura M, Hyodo K, Kawanishi M, Narikiyo T. A framework for sensorless torque estimation and control in wearable exoskeletons. In2012 12th IEEE International Workshop on Advanced Motion Control

(AMC) 2012 Mar 25 (pp. 1-7). IEEE.

22. Oh S, Kong K, Hori Y. Design and analysis of force-sensor-less power-assist control. IEEE Transactions on Industrial Electronics. 2013;61(2):985-93.

23. Wolbrecht ET, Chan V, Reinkensmeyer DJ, Bobrow JE. Optimizing compliant, model-based robotic assistance to promote neurorehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2008 Jun 10;16(3):286-97.

24. Leonardis D, Barsotti M, Loconsole C, Solazzi M, Troncossi M, Mazzotti C, et al. An EMG-controlled robotic hand exoskeleton for bilateral rehabilitation. IEEE Transactions on Haptics. 2015 Mar 30;8(2):140-51.

25. Kim H, Miller LM, Fedulow I, Simkins M, Abrams GM, Byl N, Rosen J. Kinematic data analysis for post-stroke patients following bilateral versus unilateral rehabilitation with an upper limb wearable robotic system. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2012 Jul 27;21(2):153-64.