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Self-Motion Control Exoskeleton for Upper Limb Rehabilitation with Perceptron Neuron Motion Capture

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ABSTRACT

Upper limb rehabilitation robot can facilitate patients to regain their original impaired arm function and reduce therapist' workload. However, the patient does not have a direct control over his/ her arm movement, which may lead to discomfort or even injury. This paper focuses on the development of a self-motion rehabilitation robot using Perception Neuron motion capture, where the movement of the impaired arm imitates the motion of the healthy limb. The Axis Neuron software receives the healthy upper limb's motion data from Perception Neuron. Unity serves as the simulation engine software that provides a 3-dimensional animation. ARDUnity acts as the communication platform between Unity software with Arduino. Arduino code is generated using Wire Editor, which avoids the need of the programming to be written in C++ or C#. Finally, Arduino instructs the exoskeleton motors that are connected to the impaired arm to move, following the healthy joint's motion. The forward kinematics analysis for the robotic exoskeleton has been carried out to identify its workspace. Hardware experimental tests on the elbow and wrist flexion/ extension have shown the root-mean-square errors (RMSE) between the healthy and impaired arms movement to be 1.5809° and 12.1955° respectively. The average time delay between the healthy and impaired elbow movement is 0.1 seconds. For the wrist motion, the time delay is 1 second. The experimental results verified the feasibility and effectiveness of the Perception Neuron in realizing the self-motion control robot for upper limb rehabilitation**.** The proposed system enables the patients to conduct the rehabilitation therapy in a safer and more comfortable way as they can directly adjust the speed or stop the movement of the affected limb whenever they feel pain or discomfort.

1. Introduction

Stroke is known as Cerebrovascular accident (CVA) which occurs due to lack of oxygen being supplied to the brain due to the blockage of blood flow or rupture of an artery. Paralysis or loss of muscle movement is one of the complications due to stroke, where one side of the body is not functioning well. Post stroke patients learn to increase their functional abilities by repetitive rehabilitation exercises [1]-[10] in the hospitals or rehabilitation centres. However, these procedures take so much time and need to be done repeatedly with the help of a physiotherapist. Nevertheless, the number of physiotherapists in most countries is insufficient to train the high number of stroke patients. Robotic assisted rehabilitation systems [11]-[37] can help the patients to perform the repeated exercises and reduce the dependency of the treatment on the therapists. The robotic rehabilitation system can be in the form of: (1) actuated-object device where the patient must hold the robotic tool while it makes the desired motion during the therapy and (2) exoskeleton where the users need to wear the device and it provides a pre-programmed repetitive movement for the limbs in the therapy.

Li and Cheng (2017) presented a preliminary study on the design and control of a pneumatically actuated upper limb rehabilitation device. The device is designed to help post-stroke patients to stretch their spastic upper limbs. The actuator of the upper limb rehabilitation device is fabricated by using a soft material, powered with fluid pressure, and embedded in one glove surface [15]. Guo et al. (2018) presented and evaluated the design of a soft upper limb exo-sheath that is integrated with soft fabric electromyography (EMG) sensor. The design is used for assisting stroke and spinal cord injury patients to perform rehabilitation and activities of daily living [16]. Chen et al. (2021) presented a wearable upper limb rehabilitation system with a pair of gloves, namely a sensory glove and a motor glove. It was designed and fabricated with a soft and flexible material that provides greater comfort and safety [17]. Harischandra and Abeykoon (2017) presented a bimanual rehabilitation training system that consists of two 1-DOF robots which is configured as a master-slave system [18]. Disturbance observers are implemented to make the system robust. Liu et al. (2017) studied the design of a training system for upper limb rehabilitation based on augmented reality technology so that the real and virtual environments can be interacted simultaneously by the patient [19]. Alimanova et al. (2017) presented a VR-based game for upper limb rehabilitation to motivate the patients in developing their muscle tones and increasing the precision in gestures [20]. Placidi et al. (2018) studied the implementation of a LEAP-based virtual glove for upper limb rehabilitation. It is found that Leap Motion sensors are the common sensors used in the VR-based strategies for upper limb rehabilitation [21]. Abdallah et al. (2017) designed and developed 3D printed myoelectric robotic exoskeleton for upper limb rehabilitation that can drive in real-time 3-DOF for each finger [22]. Wang et al. (2018) introduced a newly developed exoskeleton for upper limb rehabilitation with a user-centred design concept, which integrates the requirements of practical use, mechanical structure and control system [23]. Numerous works have been done in the development of upper limb rehabilitation systems as described above. However, in most of these researches, the movement of the patient's impaired upper extremity are predefined or set by the designers in the robot programming. Therefore, in most of the systems, the users have no direct control over the motion of their affected arm, which may lead to discomfort or even injuries.

Self-motion control rehabilitation system is a type of robotic-assisted rehabilitation that utilizes the master-slave concept, where the affected patient's limb is driven by his/ her healthy extremity [38]-[44]. The impaired arm that acts as the slave in the system imitates the movement of the healthy arm that serves as the master. The sensors attached to the healthy arm collect its motion data and then transmit the information to the processor, which is then used as the desired trajectory for the disabled hand to follow [38]. By this, the patient's healthy limb has direct influence over his/her unhealthy extremity's movement, speed and range of motion. Tan et al. (2020) presents a hand-assisted rehabilitation robot based on the master-slave motion concept, where the user wears a rehabilitation glove on the non-affected hand and the unhealthy hand on the opposite side mimics its movement. The doctor uses the collected data to design the patient's complete therapy plan [39]. An 18 DOF (degree of freedom) exoskeleton has been built in [40] to enable the exercise regime of the impaired hand to be controlled by the fully functioning hand. The system covers the wrist movement, and fingers and thumb flexion/extension and abduction/adduction. Virtual reality has been added to a self -motion control rehabilitation system in [41] and clinical trial has been performed on the proposed system, showing promising results. Li et al. (2010) manipulates two directly wired identical motor to develop a force sensor-less training system for the upper limb [42]. Bae et al. (2012) presents a robotic orthosis self-motion control for upper limb rehabilitation system, consisting of linear actuators, pneumatic cylinder and two electric linear motors to drive the wrist and fingers [43].

In a self-motion control rehabilitation system, the sensors on the master side plays a vital role to capture the necessary data so that the right motion instruction can be given to and reproduced by the slave side. Perception Neuron from Noitom Ltd. [44]-[50] is a commercialize inertial motion capture body suit for acquiring accurate motion data. It is easy to use, cost effective and can be utilized for various application such as animation design, health monitoring, game creation and humanoid programming. Sers et al. (2020) validates the effectiveness of the motion capture system in measuring the range of motion of the neck, thorax and shoulders [45]. Choo et al. (2022) further tested the perception neuron for full-body motion capture and compare the readings with VICON, a conventional optoelectronic motion capture system while the users perform several dynamic activities. The study reports that Perception Neuron has performed well against the VICON motion analysis system [46]. Perception Neuron has also been used for training the surgical trainees in simulations set up. The correlation between the simulation marks and body movements has been access using the motion capture device [47]. Jung (2021) applies the Perception Neuron in extracting human movement data to train wearable robots and display the movement graphically [48]. Becattini et al. (2019) had implemented Perception Neuron together with Support Vector Machines algorithm for gesture recognition [49]. Several works have been done previously in applying Perception Neuron in various fields due to its easy to use, compact design and lower cost compared to advanced vision-based motion capture systems. However, the development and feasibility of the self-motion control robot with Perception Neuron to provide the master movement that can be followed by the impaired side of the limb can be further explored.

The main objective of this study is the development of self-motion control upper limb rehabilitation system. The contribution of the work is in the implementation of Perception Neuron in the proposed self-motion control system, targeting the elbow and wrist flexion/ extension motions. The system allows the patients to control the movement of their impaired upper extremity using their healthy limb as the reference. This enables them to directly control the motion of the affected limb based on their own feedback and leads to patient empowerment and personalized rehabilitation. Perception Neuron is chosen for this application since it is able to capture the motion of the human arm with a high detail, therefore, providing a smooth movement for the impaired limb. This paper will describe the connection of the Perception Neuron device to the Axis Neuron driver that is used to receive motion data, Unity simulation engine software for animation, ARDUnity as the link to communicate Unity with Arduino that receives the motion command and drive the exoskeleton's motor. The complete system and the feasibility of the perception neuron for the self-motion control upper limb rehabilitation has been tested experimentally. The rest of this paper is organized as follows. The methods implemented in the development of the self-motion control upper limb rehabilitation system is presented in Section 2. Section 3 discusses the results on the workspace obtained from the kinematics analysis and outcomes of the experimental tests. Finally, conclusion is drawn in Section 4.

2. Methods

2.1. Self-Motion based Rehabilitation System

In this rehabilitation system, the healthy upper limb is set as a reference and the impaired upper limb is driven by an exoskeleton based on the data obtained from the healthy upper limb. The targeted motions are elbow and wrist flexion/ extension. The angular position data obtained from the healthy arm is sent to the exoskeleton prototype to move the impaired arm so that it follows the motion of the healthy side. The self-motion-based rehabilitation system consists of the Perception Neuron glove for the healthy arm and a robotic exoskeleton that is equipped with Inertial Measurement Unit (IMU) and Arduino Microcontroller board for the impaired arm. The software includes Axis Neuron, Unity, ARDUnity, Xsens MT Manager and Arduino coding. The Perception Neuron glove and Xsens IMU provide a combination of motion capture sensors suitable for capturing both hand and forearm movements. They offer an accurate motion tracking capability. The wireless data transmission from the IMU to the Xsens MT Manager software enhances the system's flexibility and ease of use. The integration between Axis Neuron and Unity allows for real-time visualization of motion capture data in a 3D environment, enhancing the user's experience and providing visual feedbacks during rehabilitation exercises. ARDUnity simplifies the interaction between Unity software and Arduino, making it accessible to users without advanced programming skills.

Referring to Fig. 1, the components in the self-motion based rehabilitation system can be explained as follows: (1) Perception Neuron glove is used to capture the motions of the healthy arm by measuring the positions in x, y, and z-axes for each joint, (2) Axis Neuron is the Perception Neuron software driver that is used to receive motion data from Perception Neuron and display them (3) Unity is a 3-dimensional (3D) simulation engine software for animation or video games that presents the movement in a 3D image and updates the angle online. It is connected to the Axis Neuron using the Unity integration package. (4) ARDUnity is a library function in Unity that serves as a communication link between Unity software and Arduino that is supported by serial communication. The advantage of ARDUnity is it does not require the programme to be written in C++ or C# languages. Instead, Wire Editor is used to generate the Arduino code. (5) Arduino software receives the motion command for the impaired arm based on the data of the healthy arm from the ARDUnity. The integration of Axis Neuron, Unity and Arduino through ARDUnity is necessary so that the acquired motion data from Perception Neuron can be visualized and transferred to Arduino in controlling the movement of the impaired arm. (6) The exoskeleton for the affected arm is controlled by the Arduino and attached with an Inertial Measurement Unit (IMU) at the forearm link so that its motion can be compared with the healthy upper limb's movement.

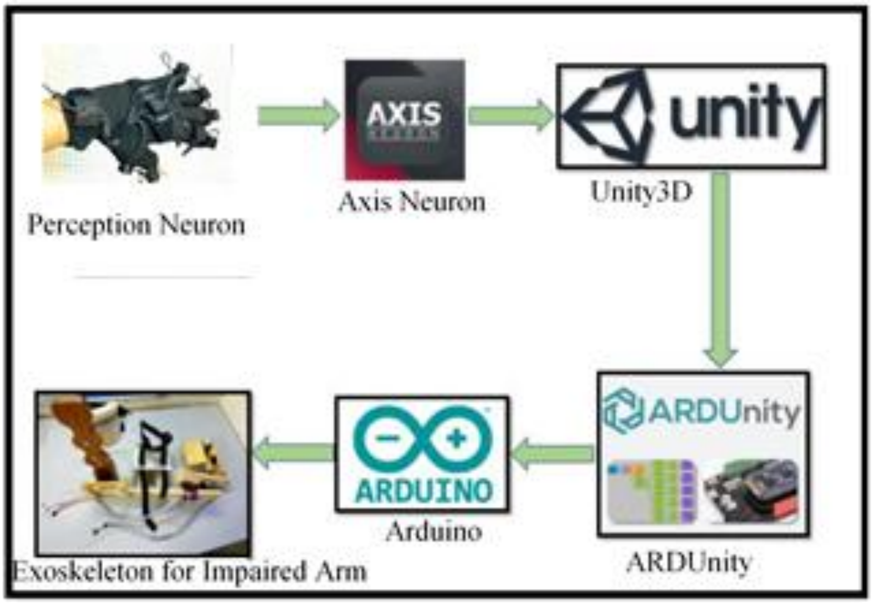

Fig. 1. Block diagram of the self-motion control upper limb rehabilitation system

2.2. Exoskeleton for the Impaired Upper Limb in the Self-Motion Controlled Rehabilitation

The exoskeleton is the upgraded and third version of the exoskeleton that had been developed in [4] and [12]. The upgraded version of the exoskeleton consists of five links which are a fixed link for upper arm, a four-bar linkage mechanism that is connected to a link for the forearm, and a set of three linkages for the 3-DOF wrist motion as shown in Fig. 2 and Fig. 3. Three servomotors act as actuators and are attached at the: (1) upper arm link for the elbow flexion/ extension motion and is connected using four-bar linkage, (2) forearm linkage for radial and ulnar deviation and (3) wrist link for wrist flexion/ extension that has been newly added in the third version of the exoskeleton. The wrist flexion/extension movement has been incorporated to allow the rehabilitation at this joint. Two arc-shaped arm holders are attached to the upper arm and forearm, and used to strap the impaired arm to the exoskeleton. A holding pole is attached at the end of the exoskeleton where the patients can hold it during the rehabilitation training. In comparison to the prototypes developed in [4] and [12], the upgraded robotic exoskeleton in this study has a higher degree of freedom (DOF) than the earlier versions.

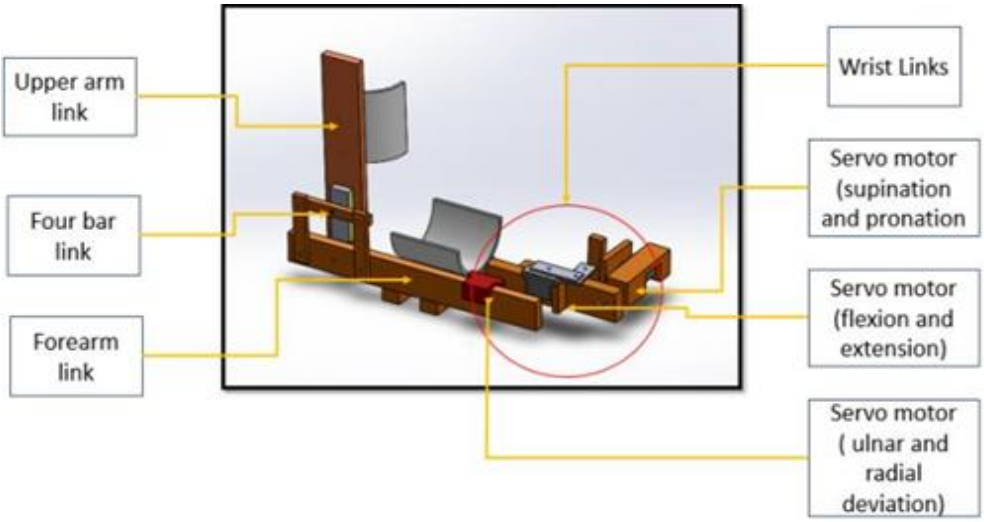

Fig. 2. Isometric view of the exoskeleton

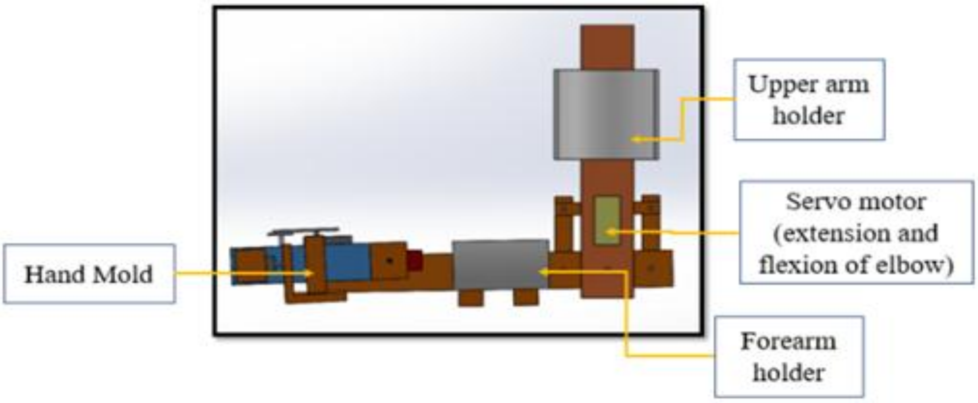

Fig. 3. Front view of the exoskeleton

The exoskeleton prototype for the impaired arm has been fabricated as shown in Fig. 4. The linkages are made of woods, the holding pole and two arc-shaped arm holders are made from 3D printing. Inertial Measurement Unit (IMU) from Xsens as shown in Fig. 5 is attached on the forearm linkage to measure its movement and compare it with the healthy arm motion. Velcro straps are used to tighten the impaired upper limb on the exoskeleton prototype. Arduino Uno Rev3 can has been connected to the computer via USB. It consists of Atmega328 microprocessor, 6 analog inputs and 14 digital inputs. All servo motors are connected to the Arduino Uno and a 240V alternating current (AC) power supply is used as the voltage source. It is converted to direct current (DC) power supply by using an adapter. The Arduino microcontroller board is connected to the laptop using USB cable.

2.3. Kinematic Analysis of the Exoskeleton

The kinematic of the exoskeleton has been analysed using the Denavit-Hartenberg (D-H) technique that systematically assigns a coordinate system to each link of the exoskeleton. The coordinate system is assigned to each link of the exoskeleton, allowing for precise kinematic modeling. The transformation matrices are computed, enabling accurate representation of each link's coordinate frame. The frame of the exoskeleton and its axis is assigned as in Fig. 6. From the frame, the D-H parameters are obtained as shown in Table 1 and are used to determine the matrix that represent each link's coordinate frame with respect to the previous link's coordinate system. The following four transformation parameters are as follows: θ_i is the angle about Z_{i-1}, from X_{i-1} to X_i, d_i is the offset along Z_{i-1} to the common normal, $a_i$is the length of the common normal, and α_i is the angle about common normal, from Z_{i-1} axis to Z_i axis, where i is the joint of the robotic arm.

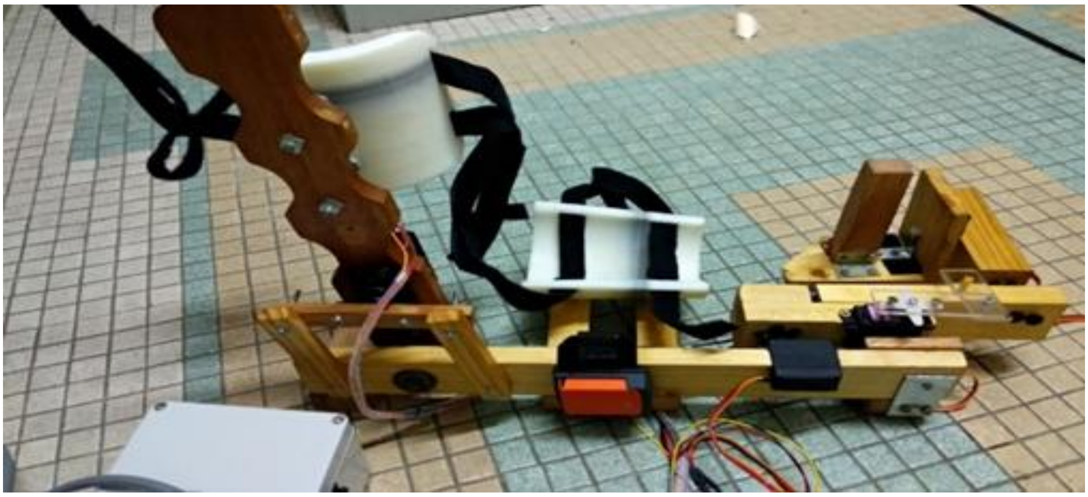

Fig. 4. Exoskeleton prototype

Fig. 5. IMU sensor, Xsens

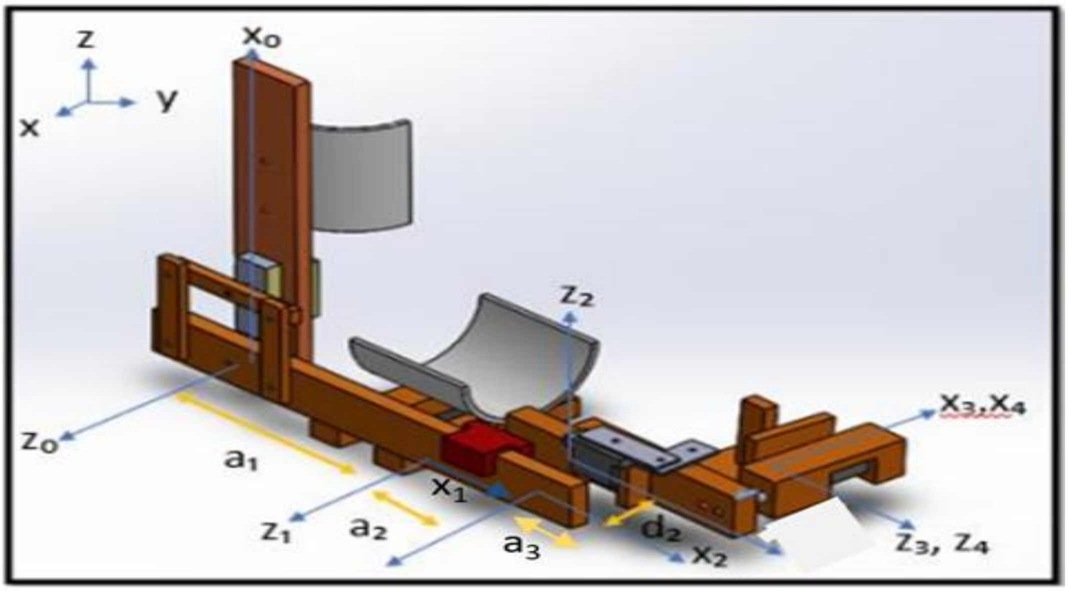

Fig. 6. Reference frame for the exoskeleton

Table 1. D-H Parameter for the exoskeleton

	D-H Parameter for the Exoskeleton			
	Θ	d	a	α
1	Θ_1	0	a_1	0^0
2	Θ_2	d_2	a_2	-90^0
3	Θ	0	a_3	90^0

Using Table 1, the transformation matrix can be obtained as

$$A_1 = \begin{bmatrix} C_1 & -S_1 & 0 & a_1C_1 \\ S_1 & C_1 & 0 & a_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, A_2 = \begin{bmatrix} C_2 & 0 & -S_2 & a_2C_2 \\ S_2 & 0 & C_2 & a_2S_2 \\ 0 & -1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad A_3 = \begin{bmatrix} C_3 & 0 & S_3 & a_3C_3 \\ S_3 & 0 & -C_3 & a_3S_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{1}$$

Therefore, the forward kinematics of the robotic arm can be described by

$$^0T_3 = A_1A_2A_3 = \begin{bmatrix} C_{12}C_3 & -S_{12} & C_{12}S_3 & P_x \\ -C_{12}C_3 & C_{12} & S_{12}S_3 & P_y \\ -S_3 & 0 & C_3 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

Where

$$\begin{aligned} P_x &= a_3C_{12}C_3 + a_2C_{12} + a_1C_1, \\ P_y &= a_3S_{12}C_3 + a_2S_{12} + a_1S_1, \\ P_z &= -a_3S_3 + d_2 \end{aligned} \tag{3}$$

It is noted that P_x, P_y and P_z are the x, y and z position of the end of the robotic arm respectively. In this work, the forward kinematics analysis of the exoskeleton will be used in studying its workspace.

2.4. Data Motion Capture Device for the Healthy Upper Limb

The data motion capture device for the healthy upper extremity consists of the Perception Neuron Glove for hand and IMU from Xsens for the forearm as depicted in Fig. 7. Perception Neuron is a small, adaptive, versatile and affordable technological equipment that can capture the movement. The modular system depends on the neuron which is known as an Inertial Measurement Unit (IMU) that consists of a three-axis gyroscope, three-axis accelerometer and three-axis magnetometer. The advantages of the system lie in the perception neuron's proprietary embedded data fusion, human body dynamics and physical engine algorithms which transfer smooth and true motion with minimal latency. The Xsens IMU consist of gyroscopes and triad accelerometers that give an output angle values in 3-dimensional orientations which are roll, pitch and yaw. The sensors operate with Xsens MT manager software. The data is wirelessly transferred to MT Manager using the router provided with IMU Xsens sensors.

2.5. Data Motion Capture Procedure for Healthy Upper Limb

The steps for capturing the motion data for the healthy upper extremity are as follows: (1) All the hardware components are checked before starting the motion capture, including the Perception Neurons, USB cable data, power supply, Perception Hub, dual pogo-pin cable and prop cable, straps and a glove, (2) Axis Neuron software is downloaded from the link: www.neuronmocap.com and installed on the laptop. The software manages and calibrates the system, and also performs basic motion capture. One of the most important features of Axis Neuron is the ability to stream the Biovision Hierarchical (BVH) data stream and export files to Filebox (FBX), (3) For USB mode, the upper part of the Perception Neurons is used to link the hub with the power supply and computer for data transmission. Another port is used for power supply mode, (4) Perception Neurons is then plugged into the glove or strapped on the human body, (5) the Hub is linked either with the gloves or body straps, (6) Axis Neuron software is then started, (7) the target device is then connected, (8) and then the motions are captured by Axis Neuron in real-time. The perception Neurons should not be used in an environment with strong magnetic interference as it can lead to significant errors in the motion capture data. Exposing the Perception Neurons to such environment for an extended period can cause magnetization.

Fig. 7. Healthy upper limb with perception neuron glove and IMU from Xsens

2.6. Integration of Axis Neuron with Unity

Data transfer via USB or WIFI can be done by integrating the Axis Neuron to the Unity software through the hub attached to the Perception Neurons as shown in Fig. 8. The steps to integrate both software are as follows: (1) Axis Neuron installer is started after downloading, (2) BVH data streaming is turned on, (3) Axis neuron is connected to Unity with online data motion, (3) Unity is started and the project file that contains the data from Perception Neurons is loaded, (7) Import button is clicked, and (8) Unity software is linked with the Axis Neuron.

Fig. 8. Interface in Unity after Unity and axis neuron integration

2.7. Integration of Unity Software with Arduino Using ARDUnity

ARDUnity is a compound word of “Arduino + Unity” , a convenient package to interact with the Arduino using Unity App. It does not require a high-level skill of C++ or C# coding. The steps to use ARDUnity are: (1) All the servomotors are connected to the respective pins, (2) Wire Editor is used to add other components (3) Arduino sketch is exported and uploaded to Arduino board as shown in Fig. 9, and (4) Unity Editor is played and ARDUnity App is connected. The programming using Wire Editor, which comes with ARDUnity package is illustrated as in Fig. 10. The programming starts with the "RotationAxisReactor" to collect the angle which the frame that has been set. Then, the angles data are sent to "GenericServo" where the input pins of the Arduino are set. The ID number is selected to differentiate between various "GenericServo" that are connected to the ARDUnity app to set the type of COM.

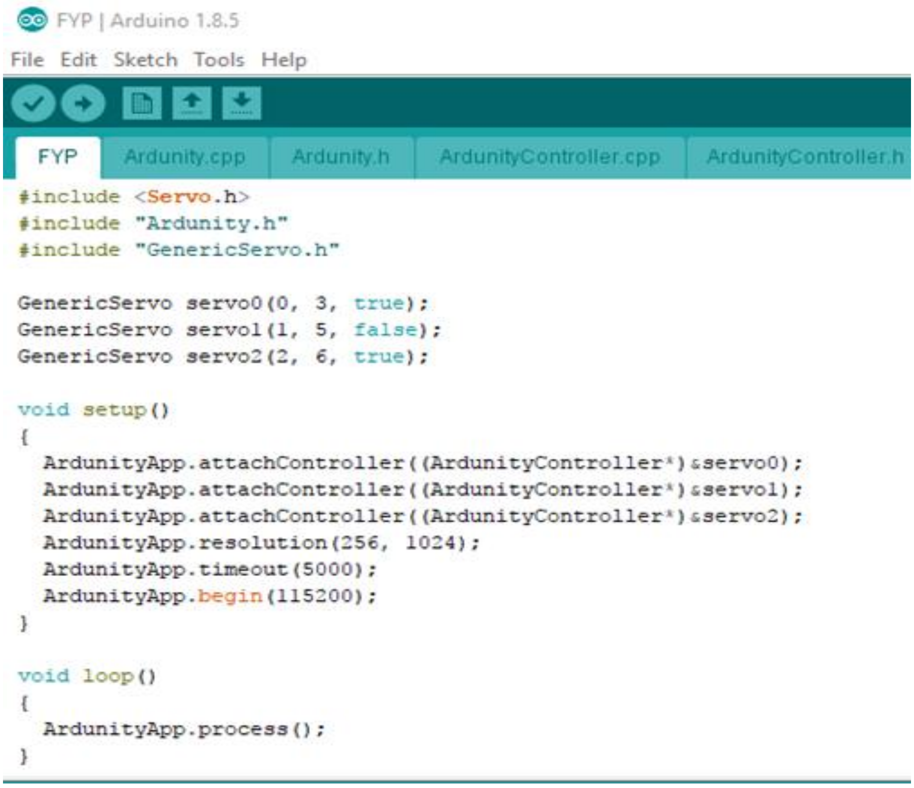

Fig. 9. Arduino programme from the export sketch features

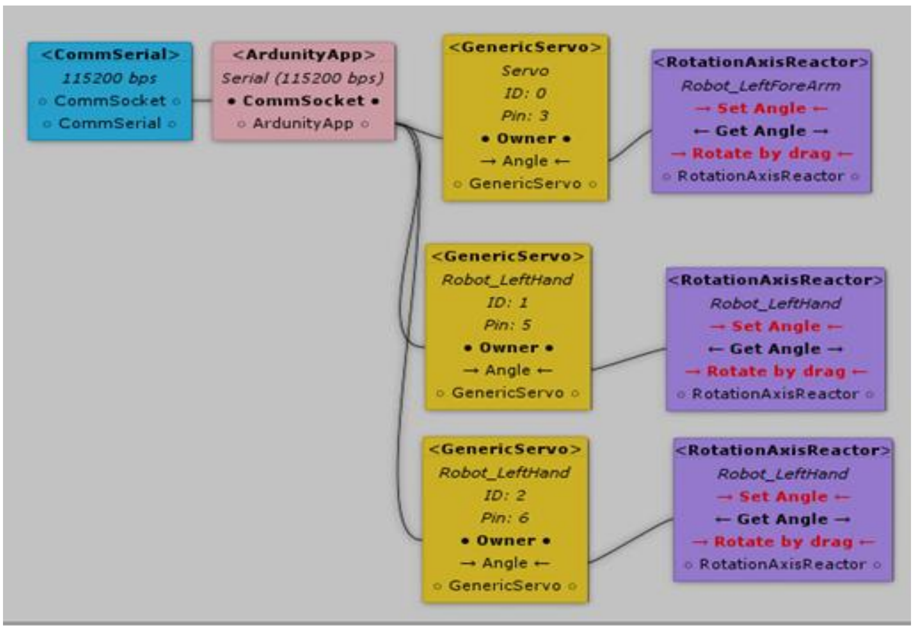

Fig. 10. Wire editor in ARDUnity

3. Results and Discussion

3.1. Results of Kinematics Analysis of the Exoskeleton

The workspace of the exoskeleton has been drawn using MATLAB software based on the kinematics relation in Section 2. The workspace for the elbow and wrist extension can be viewed in Fig. 11. The forearm link (blue line) rotates 60 degrees from -20 to 40 degrees meanwhile the wrist flexion extension (red lines) spans from 0 to 30 degrees. The 3-dimensional workspace of the exoskeleton can be viewed as in Fig. 12.

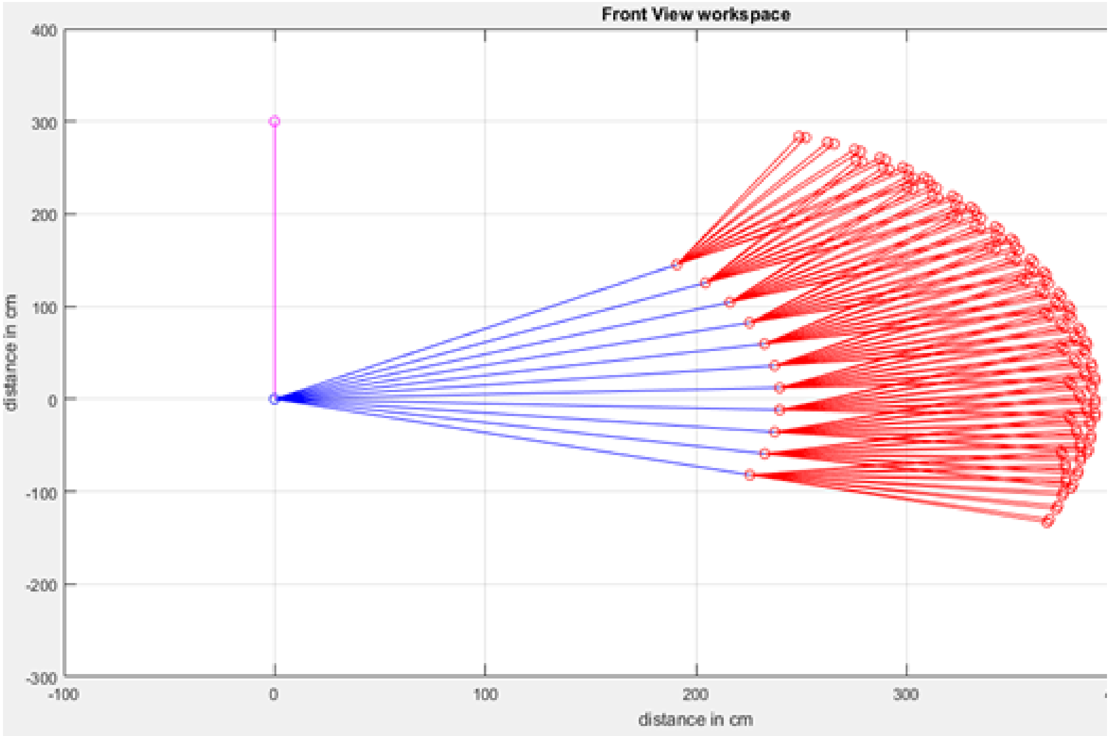

Fig. 11. Exoskeleton's workspace from the front view

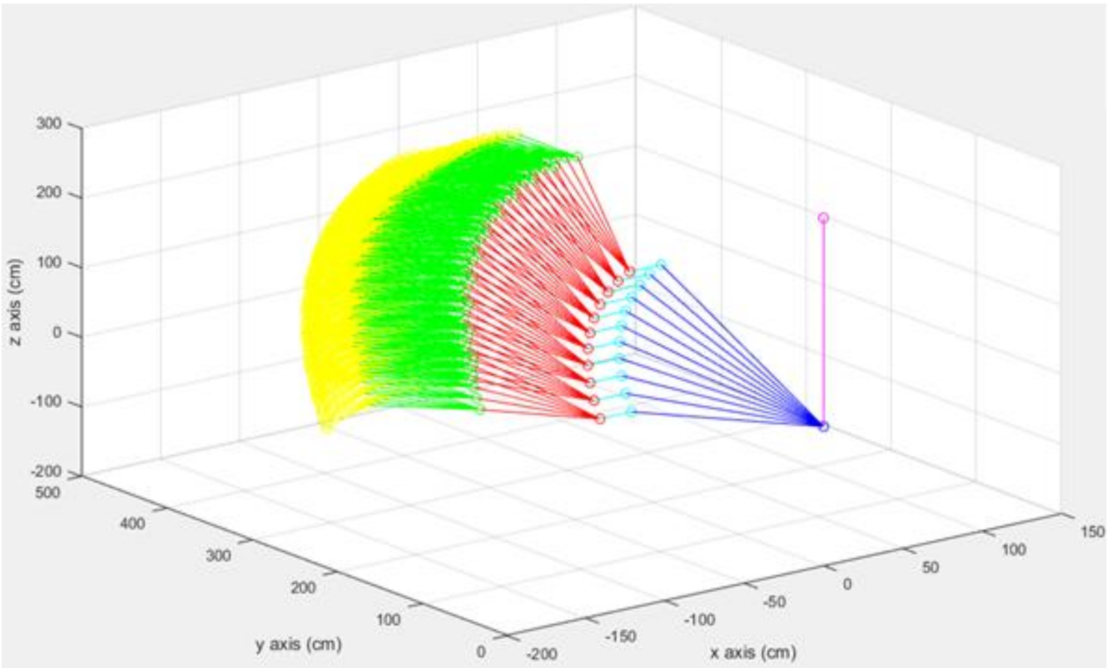

Fig. 12. Exoskeleton's workspace in 3D view

3.2. Experimental Results

The hardware experimental test has been carried out to validate the self-motion control rehabilitation system. The exoskeleton prototype was tested in assisting the impaired upper limb based on the angular displacement data that were obtained from the healthy side. The first test was carried out on elbow flexion/ extension motion. The healthy side of the elbow moves for 4 cycles between 54.5° and 72.11° as shown in Fig. 13. In the figure, the red line shows the motion of the healthy elbow while the blue line indicates the movement of the exoskeleton and impaired elbow. The root-mean-square error (RMSE) between the healthy and impaired arms movement has been calculated to be 1.5809° (0.02759 rad), which is very small. This verifies that the system has successfully driven the exoskeleton in assisting the impaired arm to move following the trajectory set by the healthy arm with a very small RMS error. The average time delay elbow movement is also very low, which is 0.1 seconds. The result validates the effectiveness of the proposed self-motion control upper limb rehabilitation system, where the exoskeleton assists the impaired elbow to move in accordance to the health arm motion.

The second test involves the wrist flexion and extension as shown in Fig. 14. The red line shows the motion of the healthy wrist while the blue line indicates the movement of the exoskeleton joint and unhealthy wrist. It can be observed from the graph that the range of the healthy wrist flexion and extension is between 32° and 85°. From the figure, it can be observed that the range movement of the exoskeleton in moving the impaired arm is between 58.4° and 83.3°, yielding an RMS error of 12.1955° or 0.21285 rad. The average time delay for the angle of the forearm is 1 second.

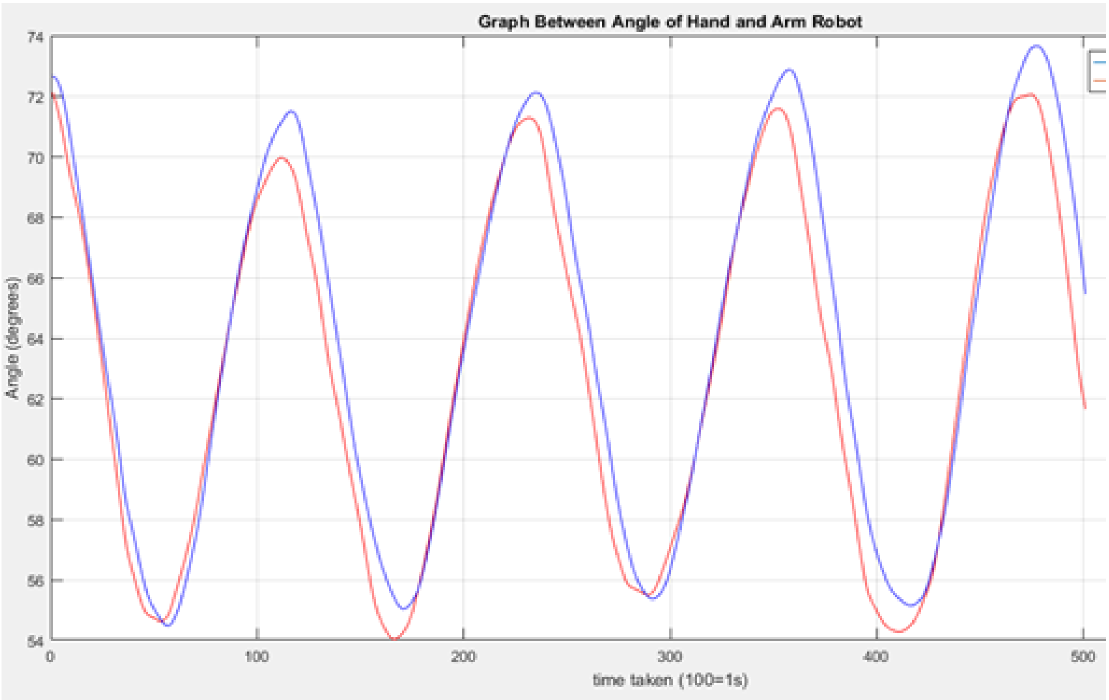

Fig. 13. Experimental test result for elbow flexion and extension

3.3. Discussions

The experimental test results demonstrates the capability of the proposed system with the utilization of Perceptron Neuron and the related software in realizing the self-motion control rehabilitation system. The healthy hand motion directly influences the movement of the developed exoskeleton in moving the impaired arm for the rehabilitation therapy. The results for self-motion control of the elbow flexion/ extension verifies that the system has successfully driven the exoskeleton in driving the impaired limb to track the healthy arm motion with a very low error and time delay. However, higher error occurs in the wrist flexion/extension compared to the elbow flexion/ extension due to the limitation in the servomotor. Further analysis on the motor load and the utilization of a proper motor to handle the load may improve the system performance. The exoskeleton prototype is also limited to 2 movements only, which are the wrist and elbow flexion/ extension motions. The replication of more complex movement may be explored in the next step of the study. The materials used for the current exoskeleton, which is made of woods and 3D printing may not offer a high level of durability and mechanical stability that are required for long-term usage and repetitive movements. Therefore, higher quality materials need to be chosen in developing the prototype. The power supply setup with a 240V AC power source and a voltage regulator for the exoskeleton may pose safety concerns. Thus, additional safety measures is necessary to ensure user protection. At this stage of study, focus has been given on the development and test of the proposed system in the laboratory. Future works need to be conducted focusing on the clinical validation or evaluation of the proposed self-motion control rehabilitation system in actual stroke rehabilitation scenarios. It is crucial to assess the system's performance and efficacy in the real-world clinical setting, considering the patients' feedback and conditions, functional improvements, practical considerations, potential risks and limitations encountered during the trials.

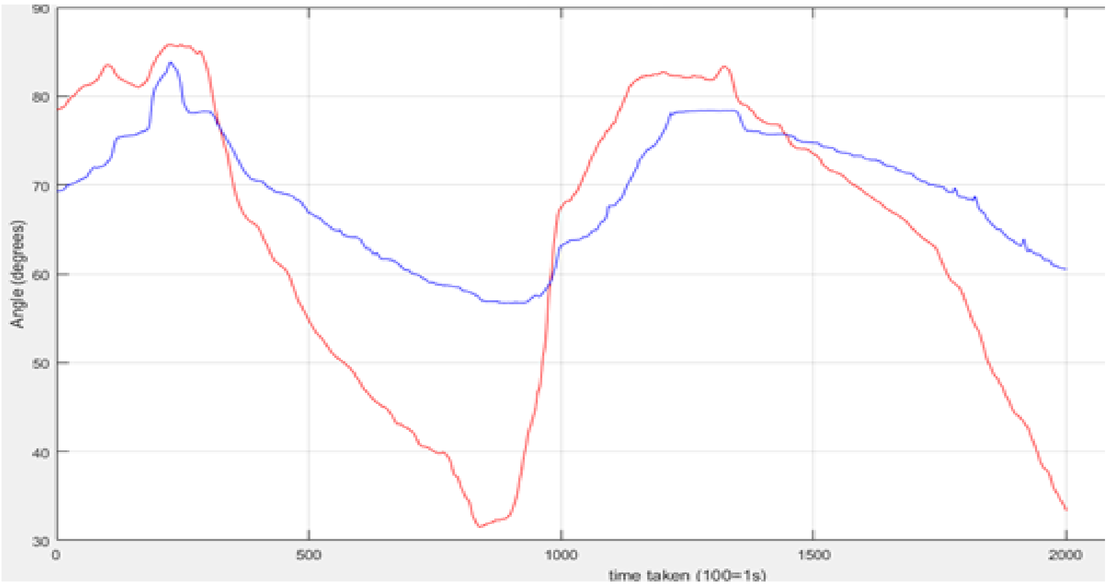

Fig. 14. Experimental test result for wrist flexion and extension

4. Conclusion

In conclusion, this paper has presented a self-motion control upper limb rehabilitation system using perceptron neuron, Axis Neuron, Unity and ARDUnity package, where the healthy side of the stroke patient controls the movement of the impaired arm. The rehabilitation system also consists of the exoskeleton prototype for the impaired upper limb, Arduino Microcontroller board for transferring the motion trajectory data from the healthy arm to the weak arm and IMU Xsens motion sensor for validating the angle tracking. The kinematic and workspace analysis of the exoskeleton has been analysed and described in this study. The experimental results have validated that the proposed system is able to realize the self-motion control of the exoskeleton with an RMSE of 1.5809° and 12.1955° and average time delay of 0.1 seconds and 1 second for the elbow and wrist flexion/extension movements respectively. The benefit of the proposed system is the patients will be able conduct his own therapy using the unaffected arm motion as the referenced for the impaired arm. As a result, they will be more comfortable and safer performing the rehabilitation exercise using the proposed system, as they will have the direct control to stop or slow down the exoskeleton whenever they are in pain or discomfort. The proposed system is also simple and easy to be used. However, this study only focuses on the system development and testing in the laboratory only. In future studies, clinical trials need to be conducted to evaluate the system's performance and its impact on rehabilitation outcomes. Its potential for personalized and autonomous therapy also needs to be further explored. The wide gap between the healthy and impaired wrist flexion/ extension motions may be due to the limitation in the servo motor. Analysis needs to be conducted in the future to determine the amount of load that the motor needs to handle so that the appropriate motor can be chosen to improve the exoskeleton's movement. The potential limitations of the Perception Neuron and Xsens IMU, such as sensitivity to magnetic interference, or limitations in capturing complex joint movements also needs to be investigated. Future works also involve increasing the number of DOF of the system, covering the motion of shoulder and finger joints, and improving the exoskeleton mechanism so that the position error between the impaired and healthy arms can be further reduced.

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