SENSOR BASED ARM REHABILITATION FOR POST STROKE PATIENTS

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Declaration of Authorship

We, Ridwan Kabir (134436) and Mohaimin Ehsan (134444) declare that this thesis titled "SENSOR BASED ARM REHABILITATION FOR POST STROKE PATIENTS" and the works presented in it are our own. We confirm that:

- This work has been done on partial fulfillment of the Bachelor of Science in Computer Science and Engineering degree at Islamic University of Technology.
- Any part of thesis has not been submitted anywhere else for obtaining any degree.
- Where we have consulted published work of others, we have always clearly attributed the sources.

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Abstract

Noise free data obtained from devices used to track human motion can be used to determine the position, orientation and motion of various parts of human body specially the limbs. These data can be used to determine a proper therapeutic intervention for those people, who face difficulties in moving the different limbs. In our research, we present a method to derive data from sensors like IMU (Inertial Measurement Unit) and Flex sensors and map them to determine the position and orientation of human arm in real time. This will help therapists to ensure proper, accurate and efficient therapeutic intervention for arm rehabilitation of post stroke patients through visualization. The visualization includes a human arm model in 3D space whose position and orientation is determined through forward kinematics using the Denavit-Hartenberg Convention and 3D transformation and rotation

Keywords:

Assistive technology, HCI, Therapeutic Intervention, Stroke Patients, Arm Rehabilitation.

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Chapter 1

Introduction

Brain stroke is a common occurrence around the globe. Due to this, people around the world suffer from paralysis of certain parts of their body. They require medical attention especially from the physiotherapists in order to regain their lost potential. In our work, we focused on a method to increase the accuracy and effectiveness of the therapeutic interventions of the arm. Using the concept of Body Area Network (BAN), also known as a Body Sensor Network (BSN), a wireless network of wearable computing devices, we developed a wired sensor network connected to a processing unit (Arduino) placed on upper-limb of the patient. Noise free data obtained from the sensors can be used to determine the position, orientation and motion of various parts of human body specially the limbs. In our research, we wish to develop a method to derive data from sensors like IMU (Inertial Measurement Unit) and Flex sensors and map them to determine the position and orientation of human arm in real time. This will help therapists to ensure accurate and efficient therapeutic intervention through visualization; which includes a human arm model in 3D space whose position and orientation is determined through forward kinematics using the Denavit-Hartenberg Convention and 3D transformation. The outcomes of this research can be an assistive technology along with conventional therapy in order to increase efficiency and accuracy of therapeutic interventions only and not to replace the care and attention, a patient requires from a caregiver. This will allow both trained and untrained caregivers to attend to the patient’s regular therapeutic interventions.

1.1 Human Motion Tracking

Continuous tracking of human motions in natural environments potentially provides more accurate and intuitive feedback than in-lab settings. At present, however, it is difficult to achieve the goal of tracking and monitoring a patient's motion at anytime and anywhere. The restriction is from the tracking facilities, such as visual motion capturing systems, are too pricy and complicated to be practically applied for home use. Besides, a feasible motion tracking in the free-living environment is also not achievable. Currently, patients are required to go to a lab or a clinic to have their treatment. An experienced clinician provides appropriate therapy based on their in-lab observations or subjective off-lab recall from patients themselves. As a matter of fact, aging people spend a large amount of time at home or walking outside. After-treatment rehabilitation is essential for patients to recover their motor functions. It is a dynamic process to correct undesired motions by facilities and experienced clinicians. A better way to evaluate the rehabilitation is using Body Sensor Networks (BSN). Continuous monitoring by BSN provides information of patients, which is critical to discover their health problem in time. Besides, it is able to track motions and position of elders and quickly respond to potential emergencies they are having. A BSN consists of wearable sensor platforms, such as physiological sensors (electromyography (EMG)), muscle sensors (Flex) and bio-kinetic sensors (accelerometer, gyroscope). Considering the tracking accuracy of a capturing system, most current research of human motion tracking is concentrated on visual tracking. We can say, Therapeutic interventions for post stroke arm rehabilitation is simple and easier to implement using wearable sensor platforms. At the same time Visualization of human arm motion can help increase accuracy and effectiveness of therapeutic interventions. If we can apply forward kinematics using the Denavit-Hartenberg convention helps track the position and orientation of human arm in real time. At the same time, a kinematic model of the human arm in 3D space was developed to track the motion and orientation using Denavit-Hartenberg convention. The drawback is that, the sensor data needed calibration to provide for long term stability.

1.2 Research Challenges and Goals

Real-time human motion tracking can be applied to numbers of biomedical applications, such as clinical gait analysis, rehabilitation, joint motion analysis and etc. There are some limitations with the devices that are used in motion tracking. For some motions the reading can be invalid. For two motions there can be same reading. There can be lag between motions and its response in the visual interface. There can be noise in the reading that is inherent with the motion tracking device.

Our goal is to overcome these challenges and create a device that will be able to get the motion tracing readings and use these readings to guide the patients to get the proper and accurate therapies. To do that we have to-

- Reduce data noises. To do this we can use complementary filters.
- Reduce the lag between the motion and the response as much as possible.
- Create a wearable wireless device with visual assistant.

1.3 Motivation

During post stroke period, one of the major problems that patients face is disorders in motor activities. One of these disorders includes limitations in arm movements. The patients in order to recover from these disorders seek therapies for a particular duration. They normally seek help from various physiotherapists.

This is sometimes costly and time consuming. In our research, we propose a system that can help the patients perform the required therapies with or without the help of any attending physician accurately and efficiently. Our proposed system uses accelerometer and flex sensors to measure the patient's performance and guide them to perform the therapies with greater accuracy. We mainly focused our goal on the post stroke arm disorder patients. We use Inertial Measurement Unit (IMU) and other methods to get the reading of their arm, elbow, wrist and shoulder movement like- shoulder abduction, shoulder adduction, arm flexion, arm extension, inertial arm rotation etc. We use this reading to give a visual interface to guide the patients in order to perform the required therapies with greater accuracy.

1.4 Problem Statement

"To develop a visual assistive technology for improving the accuracy and effectiveness of therapeutic arm interventions for post stroke patients by tracking the motion of the arm with the help of Body Sensor Networks (BSNs) and applying forward kinematics on a kinematic model of human arm in 3D space".

1.5 Related Works

- **Virtual Reality Based Post Stroke Arm Rehabilitation**

A VR-based system using a Cyber Glove and a Rutgers Master II-ND haptic glove was used to rehabilitate four post-stroke patients in the chronic phase. Each patient had to perform a variety of VR exercises to reduce impairments in their finger range of motion, speed, fractionation and strength. Patients exercised for about two hours per day, five days a week for three weeks. Results showed that three of the patients had gains in thumb range (50-140%) and finger speed (10-15%) over the three weeks trial. All four patients had significant improvement in finger fractionation (40-118%). Gains in finger strength were modest, due in part to an unexpected hardware malfunction. Two of the patients were measured against one-month post intervention and showed good retention. Evaluation using the Jebsen Test of Hand Function showed a reduction of 23-28% in time completion for two of the patients (the ones with the higher degrees of impairment). A pretension task was performed 9-40% faster for three of the patients after the intervention illustrating transfer of their improvement to a functional task.

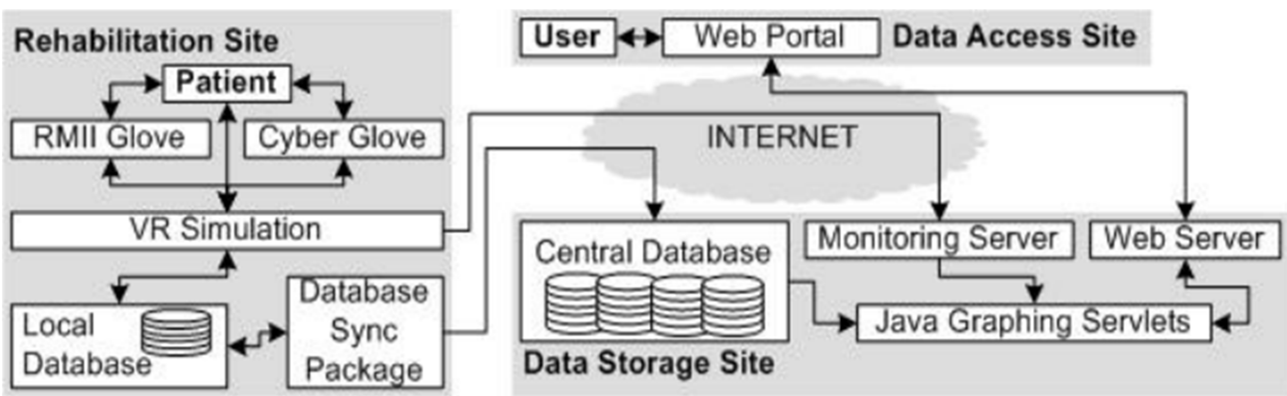


Figure 1: Rehabilitation Architecture

In this procedure, RMII Glove (Rutgers Masters II) haptic glove is used along with Cyber Glove. Virtual Reality Simulation is used as Virtual Interface. The patient wearing the RMII glove is told to touch the object in the virtual reality. When he/she touches the object, a vibrational feedback is returned indicating the object is with the hand vicinity.

The problem of using this procedure is –

I. It doesn’t provide any accurate measurement of the patients arm movement.
II. It cannot give any expert opinion in case of emergencies.
III. Replaces therapist with a device.
IV. Central database server may fail any time.

- **Arm rehabilitation with a robotic exoskeleton in Virtual Reality**

Several studies demonstrate the importance of an early, constant and intensive rehabilitation following cerebral accidents. This kind of therapy is an expensive procedure in terms of human resources and time, and the increase of both life expectance of world population and incidence of stroke is making the administration of such therapies more and more important. The development of new robotic devices for rehabilitation can help to reduce this cost and lead to new effective therapeutic procedures.

In this paper we present an exoskeleton for the robotic assisted rehabilitation of the upper limb. This article describes the main issues in the design of an exoskeletal robot with high performance, in terms of back drivability, low inertia, large workspace isomorphic to the human arm and high payload to weight ratio. The implementation of three different robotic schemes of therapy in virtual reality with this exoskeleton, based on an impedance control architecture, are presented and discussed in detail. Finally the experimental results of a preliminary evaluation of functionality of the system carried out on one patient are presented, and compared with the performance in the execution of the exercise obtained with healthy volunteers. Moreover, other preliminary results from an extended pilot clinical study with the L-Exos are reported and discussed.

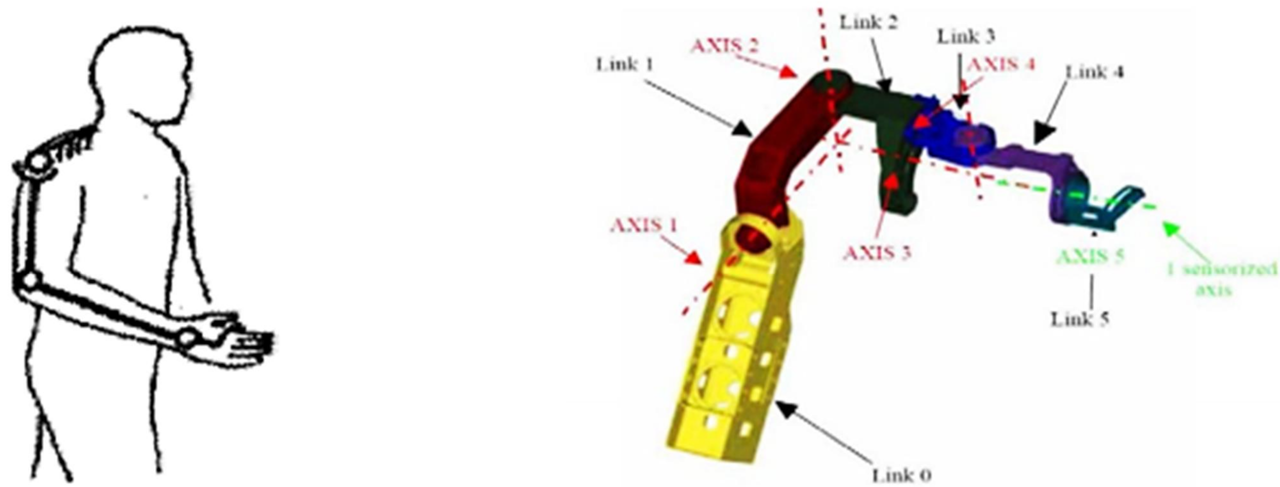


Figure 2: Exoskeleton System and General Kinematics of L- Exos

An exoskeleton is used for robotic assistance for the upper limb .L-Exos also known as Light Exoskeleton, designed as wearable interface used as the input for the system. Serial kinematics is used alongside the input of L-Exos from virtual reality (VR). This system can provide accurate, persistent and easy to implement hand rehabilitation technique. The problem of this procedure is-

- The system is costly.
- The system is too heavy; so fixed to only one location.
- The system can cause damage to patients if not given proper care.

1.6 Contribution

The major contributions of this dissertation are focusing on addressing the research challenges we mentioned. The details are specified as follows.

- A wearable human body motion tracking system is developed based on BSN consists of previously developed IMUs and other sensors. These sensors are attached to body segments and they measure the limb motions after a well-designed calibration procedure.
- A visual interface which completes the goals of arm posture mapping and axis alignment. The visual interface is based on 3D human arm modeling. The interface is able to guide the patients in order to find out what steps to establish the basic motor movements like a normal healthy person.
- The communication between the motion tracking unit and the interfacing PC will be wireless so that the patient can move at ease with the unit and analyze every movement they need.
- This visual interface can ensure effective and accurate therapeutic interventions.
- The complexity of the device is reduced; it much easier to use than any Vision based monitoring system.
- Forward kinematics is applied using the sensor data to detect orientation and position.

1.7 Structure of the Thesis

This book consists of six chapters in total. These 6 chapter gives the detailed description of our procedure of rehabilitation of arm for post stroke patients.

Chapter one includes abstract, introduction, motivation, contribution, related works (Virtual reality based post stroke arm rehabilitation and Arm rehabilitation with robotic exoskeleton in Virtual Reality), Problem Statement, Research goals and challenges etc.

Chapter two includes the formulation of the problem, Kinematics of the human body, Body motion reconstruction, System calibration, Estimation of Arbitrary IMU placement, Estimation Body Limb length etc.

Chapter three consists of background study for the research, different movements of shoulder, elbow, fingers and wrist, Kinematics of human model arm, DH conventions.

Chapter four includes proposed approach, DH parameters, Complimentary Filters, DH matrix, Visualization and challenges.

Chapter five includes experimental setup, Device Description, Interfacing Sensors with Arduino, Connection of IMUs, Connection of Flex Sensors, Procedure of the experiment etc.

Chapter six consists of experimental results of all the arm monument positons, analysis of these results and evaluation is done of the experiment.

Chapter seven includes conclusion and future works; also it has the interface design of our system.

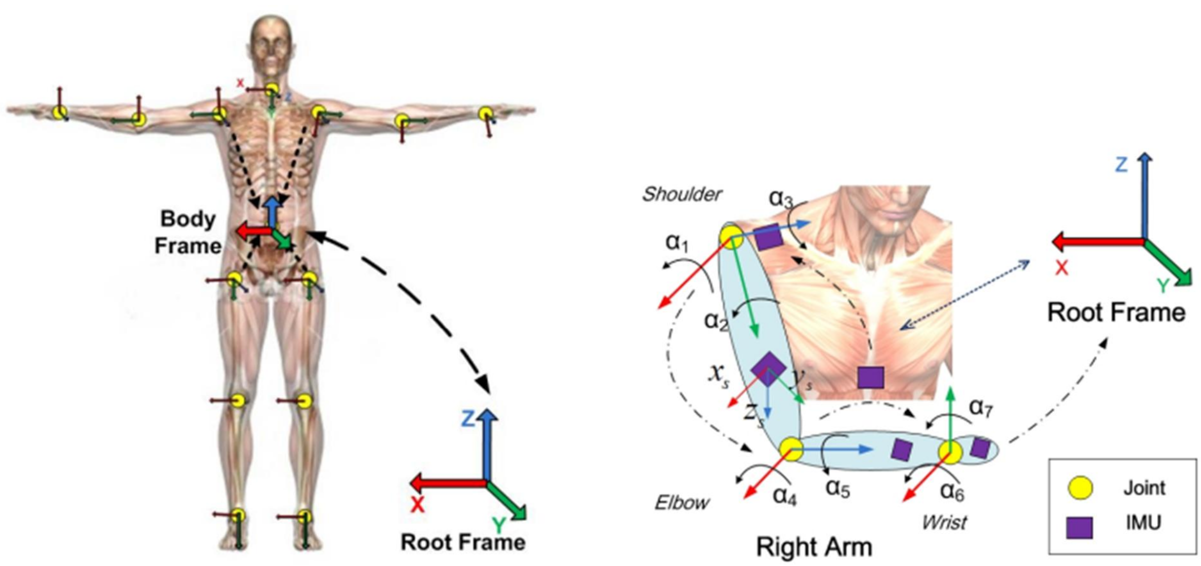
At last there are references of the resources we used for this research.

Chapter 2
Problem Formulation

Real-time human motion tracking has been applied to many applications in biomedical areas: clinical gait analysis, exercise rehabilitation, fall detection, biomechanical analysis of joints and etc. Several tracking technologies, such as mechanical tracking, magnetic tracking and visual tracking have been available for years. However, these tracking technologies lack the capability of tracking in free-living environments. Inertial tracking can track human motions in daily life with less intrusion.

2.1 Kinematics of Human Body

A human body is modeled as an articulated model, which consists of 15 rigid body segments, 14 joints and 38 DoFs. It includes torso (waist-neck part and waist-hip part), head, upper limbs and lower limbs, as are shown in Figure 3.



(a) Human full body model with joint coordinates

(b) Kinematic modeling of right arm with IMUs

Figure 3: Human Body Modeling

Human upper limb includes upper arm, forearm and hand, which has 10 DoFs in total. Taking the right arm as an example. Shoulder is described as a ball and socket joint with 6 DoFs: 3-DoF rotations and 3-DoF translations. Rotation angles are assigned to flexion-extension α1, internal-external α2 and abduction adduction α3 rotations. Elbow is modeled as 2 hinge joints with non-intersecting axes. Therefore, it is described by 2 DoFs: flexion-extension α4 and pronation-supination α5 rotations. Wrist is modeled as an ellipsoid joint with 2 DoFs: flexion-extension α6 and radial/ulnar deviation α7 rotations. For the left arm, similarly, rotation angles α8 ~ α14 are assigned to axes of shoulder, elbow and wrist joints.

Torso provides the orientation of body and it includes 2 joints: neck has 3 DoFs and waist is also considered to have 3 DoFs, so that the spinal movements can be simplified as the rotations around waist joint. Because developed system does not consider the movements of head, there is no IMU corresponding to the neck. Rotation angles α15 ~ α17 are assigned to waist joint.

Lower limbs have similar structure as upper limbs but relatively distinct functionalities; in fact, lower limbs perform less complicated motions than upper limbs. Here takes the right leg as an example, hip joint has similar structure as shoulder with 3-DoF rotations: flexion-extension α18, internal-external α19 and abduction-adduction α20. Knee joint has only 1 DoF, flexion-extension α21. Ankle joint has a complicated anatomy as introduced in the work of Lundberg, thus without impact tracking accuracy, it is simplified as 1 DoF flexion-extension α22 rotation. For the left leg, the assignment of rotation angles are from α23 to α27.

In order to reduce the complexity when modeling, the body parts are simplified as rigid bodies. When analyzing each joint, different axes along adjacent segments are regarded as intersect at the joint center. To be more specific, for example, the forearm pronation-supination movements are considered around the same center of elbow flexion-extension movements, ignoring the physiological fact that these two axes have no intersection and are not orthogonal. This simplification inevitably brings some errors to IMU placement estimation. Fortunately in our well designed calibration procedure, random IMU placement would not affect tracking results so that the accuracy can be guaranteed.

2.2 Body Motion Reconstruction

The proposed body motion tracking system mounts wireless IMUs on the main body segments to capture their movements. The coordinates of IMUs on the human arm and leg (feet are excluded) are defined as shown in Figure 4. In the figure, four IMUs are mounted on the arm to capture arm movements: one is attached to upper arm near the elbow, over the distal homers to measure shoulder rotations; one is attached to scapular to measure position change of shoulder joint; one is positioned over the distal flat surface of radius and ulna, corresponding to elbow joint movements; one is mounted on the dorsal hand surface to captured hand movements.

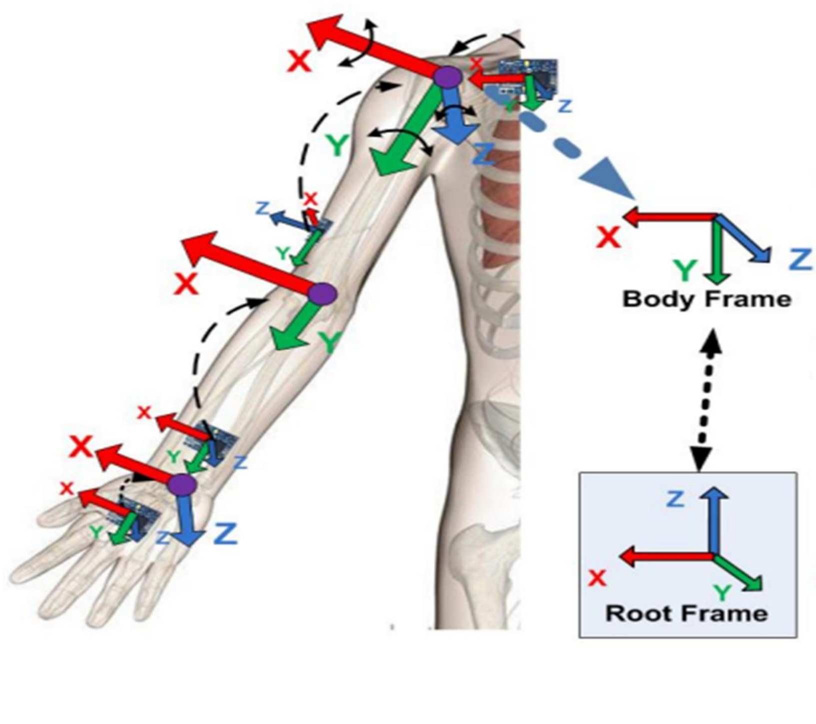


Figure 4: IMU position on Arm

2.3 Estimation of Arbitrary IMU Placement

Mounting an IMU on the human body is recurrent and an accurate position of IMU is highly demanded to be guaranteed. Since it is not expected that the subjects could place the IMU on the same position every time, a calibration procedure for estimating the position when it is randomly positioned can be considerable helpful for tracking. A more reasonable way to estimate the position of IMU is introduced in this section, compared with measuring the distance by measuring instruments. According to the fact that the rotation of human limb is a synthetic action of more than one bone, therefore, human limb movement is considered as a cylinder rotating around various axes. Although the simplification would not remove the errors caused by human muscle sliding and soft tissue artifact, the accuracy is acceptable for tracking human body motion. By rep eating human limb rotations around each axis, stable sampling from inertial measurements averages the distance between joint center and IMU, and further, estimates spatial position of the IMU. The random position estimation is designed for initializing the motion tracking, thus, the tradeoff between adding complexities to calibration procedure and improving the accuracy of body tracking system is worthwhile. When an IMU is mounted on the body and ready to initialize the system, adjacent limbs are required to hold still and the target limb rotates repeatedly around corresponding joint solely.

2.4 Estimation of Body Limb Length

Another critical part of the calibration procedure is to estimate the length of human limbs. Since the twists and exponential maps presented above need the position of adjacent joint to maintain the integrity of human limb and connectivity of limbs, an accurate estimation of human limb length will guarantee excellent results of human motion tracking. Although human body limbs are simplified as rigid bodies, measuring the length manually causes more errors than applying inertial estimations which achieve high precision from IMU measurements. Therefore, an IMU based method for estimating the body limb length is developed by employing the twist representation. Inertial measurements provide changes in spatial position and attitude, and with estimated IMU position, body limb length is calculated by solving the spatial relation of two connected body limbs. In order to assure the stability of estimation results, subjects are required to extend their limbs and swing gently around certain joint.

The length of lower arm can be calculated when extend lower arm and hand, swinging around elbow joint. For any human body limb, it is able to be estimated by extending and swinging around its joint. When the length of body limbs and position of IMUs are estimated, following motion tracking technique will apply those estimates to reconstruct.

Chapter 3

Background Study

In order to develop the appropriate therapeutic visualization of arm movement, it is first necessary to have an insight into the related therapeutic interventions that are currently provided by therapists for arm rehabilitation. Most of the time, a stroke patient suffers from mild or full paralysis of forelimbs. As a result, the movements which are easy for a healthy person, becomes very difficult to perform for a stroke patient. Some of these interventions include shoulder flexion-extension, horizontal abduction-adduction, internal-external rotation, elbow-joint flexion–extension, wrist and fingers flexion–extension, lower arm pronation and supination. So, there are in total of six fundamental motion of the human arm.

The first pair of the six basic movements is, flexion and extension. These movements occur in many joints in the body, including head, trunk, shoulder, elbow, hip and knee. Flexion is a bending movement that decreases the joint relative angle between two adjacent segments. Lifting the forearm up at the elbow is an example of elbow flexion. Extension is a straightening movement that increases the joint relative angle between two adjacent segments.

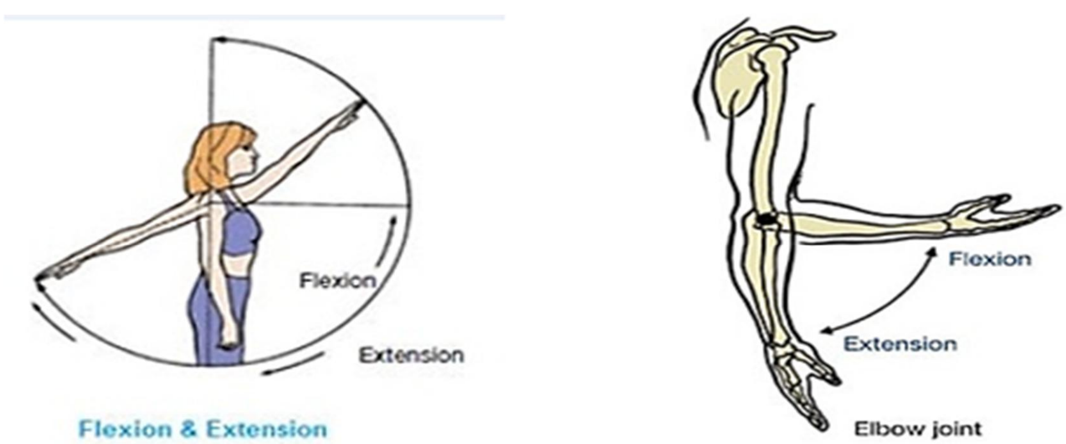


Figure 5: Flexion and Extension

The second pair of movements is abduction and adduction. These movements are not as common as flexion and extension. They occur in the scapula, shoulder, wrist, and hip joints. Abduction is a movement away from the midline of the body. Raising an arm out to the side of the body is an example of abduction. Adduction, on the other hand, is the return movement of the segment back toward the midline of the body.

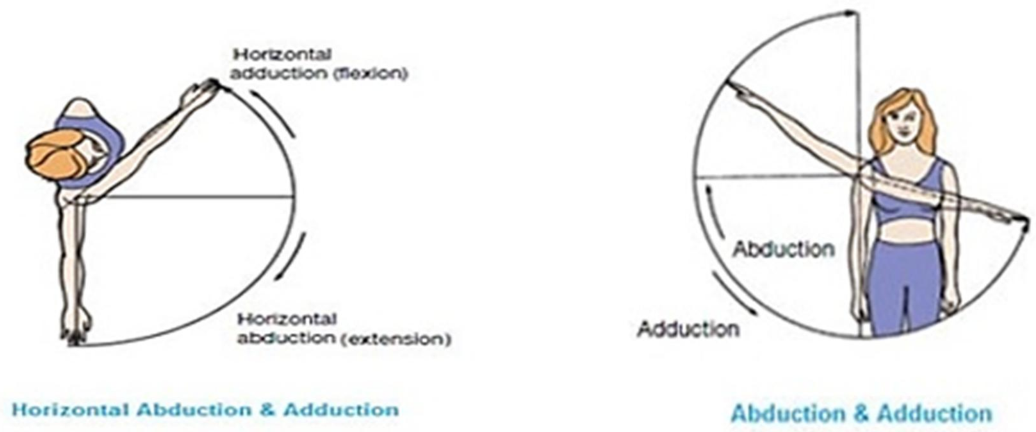


Figure 6: Abduction and Adduction

The third and last pair of basic movements is segment internal and external rotation. They occur in the head, trunk, shoulder, hip and knee joints. Internal rotation occurs when the segment rotates about the vertical axis toward the midline of the body. External rotation is the opposite movement away from the body midline.

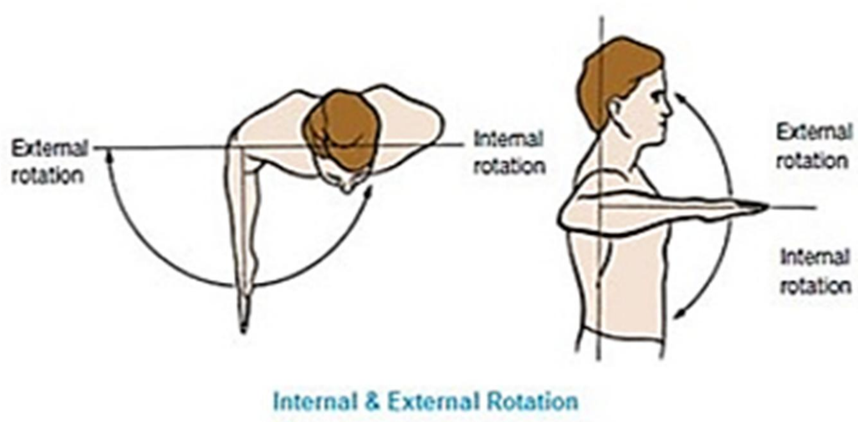


Figure 7: External and Internal Rotation

Another movement that falls under flexion and extension is elbow flexion and extension and wrist flexion and extension.

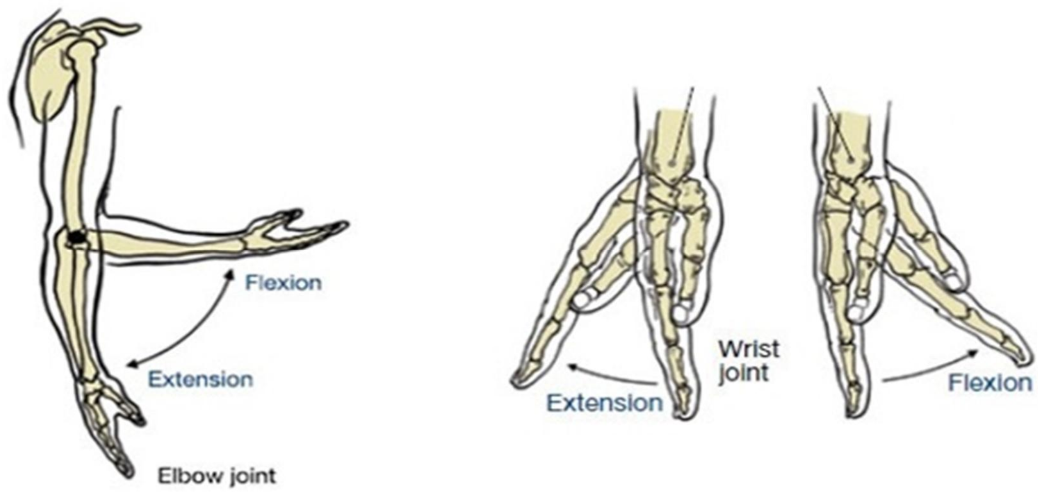


Figure 8: Elbow and Wrist Extension and Flexion

3.1 Arm Movements

Arm movement can be divided in to several parts; like- shoulder movement, Elbow, wrist and finger movement. The table below maps every actions of shoulder, primary muscles involved, the sensor that can be used to measure the data and what that shoulder action would look like.

Action of the Shoulder	What the Action Looks Like?	Primary Muscles	Sensor(s) Involved
Shoulder abduction	Lift arms out to the side	Deltoid: all fibers and supraspinatus	Myoware, Accelerometer.
Shoulder adduction	Lower arms to the side	Pectoralis major and latissimus dorsi	Myoware, Accelerometer
Shoulder flexion	Lift arms in front	Pectoralis major, and anterior fibers of the deltoid	Accelerometer

Shoulder extension	Return (lower) arms from shoulder flexion or lift arms behind	Latissimus dorsi, teres major ("little lat")	Accelerometer
Internal shoulder rotation	From the anatomical position, rotate arm so that the elbow faces forward. This action at the shoulder can occur when arm is in different positions (flexion, abduction, etc.).	Subscapularis Latissimus dorsi and pectoralis major	Accelerometer
External shoulder rotation	From a position of internal shoulder rotation, rotate arm so that the elbow faces backward. Also, anatomical position requires the shoulders to be in external rotation. This action at the shoulder can occur when arm is in different positions (flexion, abduction, etc.).	Infraspinatus and teres minor	Accelerometer
Horizontal abduction	For the start position, lift arm in front. The action occurs as the arm is moved out to the side.	Latissimus dorsi and posterior fibers of deltoid	Accelerometer
Horizontal adduction	From the starting position, lift arms out to the side. The actions occurs as the arm is moved in front.	Pectoralis major and anterior fibers of deltoid	Accelerometer

Table 1: Shoulder Movements

Again there are elbow, wrist and finger movement that are to be considered. The below table shows us the action performed on elbow, finger or wrist, what that action look like, Primary muscles and the sensors that can be used to measure movement.

Action of the Elbow and Wrist	What the Action Looks Like?	Primary Muscles	Sensor(s) Involved
Elbow flexion	Bend elbow	Biceps brachii	Myoware
Elbow extension	Straighten elbow	Triceps brachii	Myoware
Wrist flexion	Bend palm towards forearm	Wrist flexors	Flex Sensors
Wrist extension	Bend the back of hand towards forearm	Wrist extensors	Flex Sensors
Finger flexion	Close all fingers and form a fist	Flexor digitorum profundus and superficialis muscles	Myoware, Flex sensors
Fingers extension	Relax all fingers	Flexor digitorum profundus and superficialis muscles	Myoware, Flex sensors

Table 2: Elbow, Wrist and Finger Movements

3.2 Kinematics Model of Human arm

Kinematics is the study of the motion of different parts of the human body without taking into consideration, the causal force. This includes the motion of the upper arm with the shoulder joint as the reference frame, motion of the lower arm with reference to the elbow joint and the wrist joint with respect to the elbow joint, while the root frame being the shoulder joint. So the motion of human arm can be represented using the forward kinematics chain. This can be represented using the well-known and widely used Denavit Hartenberg convention.

In our case, the human arm can be expressed as a system of rigid segments joined together via the joints along the arm i.e. the shoulder joint, the elbow joint and the wrist joint. The rigid segments indicate the lengths of the upper and the lower arms.

The shoulder joint is capable of rotating about the 3- axes of motion and thus the IMU is capable of tracking the rotation of the upper arm about any of the three axes and map the link in the 3D space accordingly. On the other hand, the elbow joint acts as a hinge that can move inwards and outwards and thus the flex sensor is enough measure the elbow angle. As the upper arm and the lower arm are joined together at the elbow joint, the motion of the upper arm displaces the lower arm accordingly and the effect goes along the chain all the way down to the wrist.

Thus the detection of the elbow bend angle is independent of the position and orientation of the upper arm and now we can map the system with the Denavit Hartenberg parameters, also known as DH parameters, as defined by the Denavit Hartenberg convention.

3.3 Denavit Hartenberg Convention

To obtain a standard procedure for describing position and orientation angle of each link relative to its adjacent links, it is customary to attach a frame or coordinate system rigidly to each link. The position and orientation of one frame is then described with respect to its neighbor and eventually with respect to the reference frame. The convention of attaching frames to different links was proposed by Denavit and Hartenberg in 1955 and has been used since then in the analysis and control of robotic manipulators. The procedure of attaching frames to links in a kinematic chain is as follows:

I. Assign a base co-ordinate system to some stationary reference : X_0, Y_0, Z_0.
II. Attach a coordinate system to each of the links extending out of the reference. Frame X_i, Y_i, Z_i is attached to link i using the following conventions :-
    a. Align Z_i with the axes of rotation of the i^{th} joint.
    b. Establish X_i along the common perpendicular of both Z_i andZ_{i+1}.
    c. Establish Y_i to complete the system according to the right hand rule.
III. For the last link with the frame, assign X_n freely.

For each pair of consecutive links, represented by their associated coordinate system, there are four parameters needed to determine the relative location of these two systems.

I. The first parameter is the link length a_i , which is the shortest distance from Z_i to Z_{i+1} measure along the common normal X_i.This is not necessarily the anatomic length of the body segment.

II. The second parameter is the link twist α_i which is the angle from Z_i to Z_{i+1} , measured about the X_i axis.

III. The third parameter is the distance from $X_{i-1}$to X_i measure along the Z_i axis, and is known as the link offsetd_i.

IV. The last and fourth parameter is the joint angle θ_i and it is the angle from X_{i-1} toX_i, measured about the Z_i axis.

Chapter 4

Proposed Approach

This section includes our proposed approach for "Post stroke arm rehabilitation". The approach we are proposing using sensors and forward kinematics is shown below using a diagram.

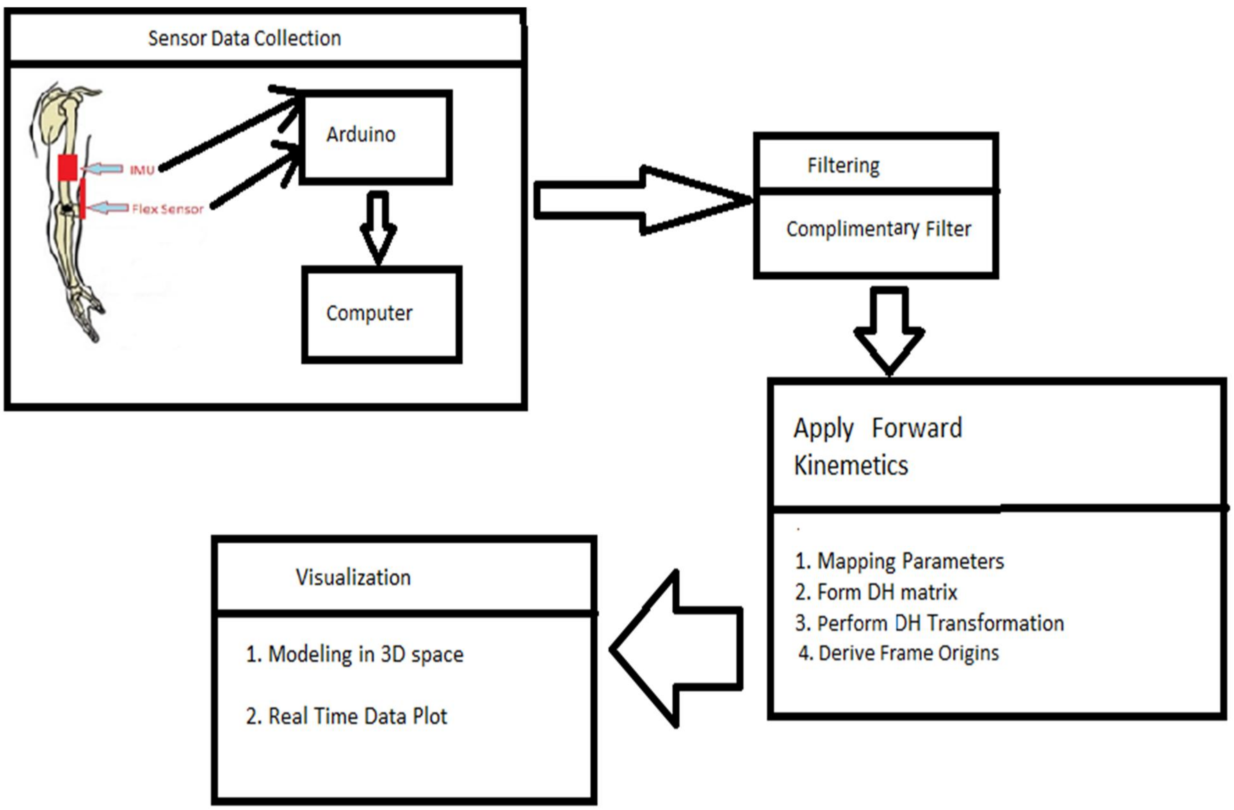


Figure 9: System Architecture of the Proposed System

4.1 DH Parameters

The data from the sensors are used to map them to the DH parameters according to the kinematic model of the human arm developed for our system as shown in figure-10.

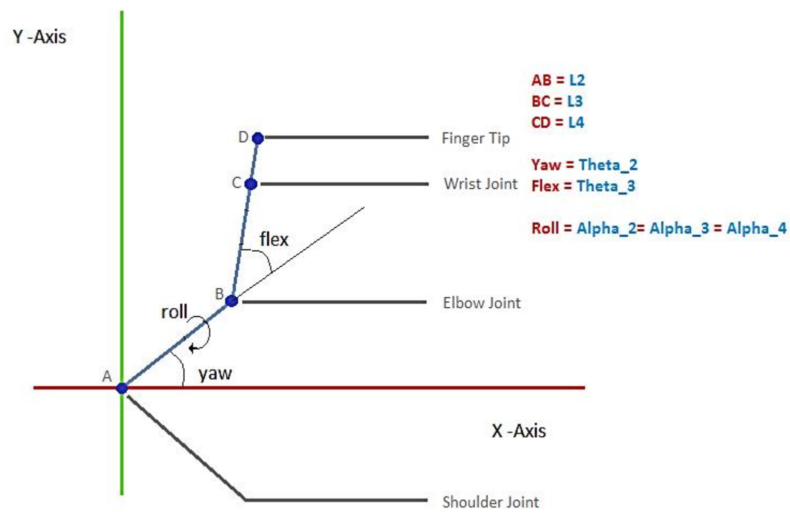


Figure 10: Kinematic Model

The human arm in our system is modeled as a set of lines joined together and manipulated by the DH matrix formed by using the DH parameters.

L_1, L_2, L_3, L_4 -are the links that represent the human arm. L_1 is attached to the root frame and has zero length. The links L_1, L_2 are coincident i.e. they share the same reference frame. L_2 -represents the upper arm, L_3 represents the lower arm and L_4 represents the wrist. The lengths of these links do not have to match the anatomical length of the patient's arm. This value can be chosen arbitrarily for desired visualization.

	a	α	d	θ
L_1	0	0	0	0
L_2	Upper arm	Pitch (y –axis)	0	Negative Yaw (z –axis)
L_3	Lower arm	Pitch (y –axis)	0	Flex sensor
L_4	Wrist to finger tip	Pitch (y –axis)	0	0

Table 3: Mapping of DH Parameters

4.2 Complimentary filters

The data received from the sensors need to be filtered as there are potential problems with the inertial measurement unit. As the IMU is a combination of both the accelerometer and gyroscope, the problems related to the accelerometer and the gyroscope are mentioned below.

- **Problems with accelerometer**
  As an accelerometer measures all forces that are working on the object, it will also see a lot more than just the gravity vector. Every small force working on the object, then the forces that drive the system will be visible on the sensor as well. The accelerometer data is reliable only on the long term, so a "low pass" filter has to be used.
- **Problems with the gyroscope**
  It is very easy to obtain an accurate angular measurement from the gyroscope that is not susceptible to external forces. The problem lies elsewhere. Because of the integration over time, the measurement has the tendency to drift, not returning to zero when the system went back to its original position. The gyroscope data is reliable only on the short term, as it starts to drift on the long term.

- **Introducing the complementary filter**

  The complementary filter gives us a "best of both worlds" kind of deal. On the short term, we use the data from the gyroscope, because it is very precise and not susceptible to external forces. On the long term, we use the data from the accelerometer, as it does not drift. In its most simple form, the filter looks as follows:

$$\theta_t = hpc * (\theta_{t-1} + \; gyro_t * \delta) + lpcacc_t$$

Where,

θ_t = Filtered angle
θ_{t-1} = Previous angular reading
δ = Sample rate
$gyro_t$ = Current gyro reading
acc_t = Acceleration data
hpc = High pass constant
lpc = Low pass constant

The gyroscope data is integrated every time-step with the current angle value. After this it is combined with the low-pass data from the accelerometer (already processed with atan2). The constants (0.98 and 0.02) have to add up to 1 but can of course be changed to tune the filter properly.

4.3 DH Matrix

To relate the i^{th} frame to its adjacent frame $(i-1)$, we perform four transformations:

I. Rotate about X_i , an angle α_{i-1} to make the two co-ordinate systems coincide.

II. Translate along X_i , a distance a_{i-1} to bring the two origins together.

III. Rotate about Z_i , an angle θ_i to align X_i and X_{i-1}.

IV. Translate along Z_i , a distance d_i to bring X_i and X_{i-1} into coincidence.

Each of these four operations can be expressed by a basic rotation-translation matrix and the product of these four transformation matrices yields a composite matrix ${}^{i-1}_{\ i}T$, known as the DH transformation matrix which defines frame i to its adjacent frame $(i-1)$.

$$ {}^{i-1}_{\ i}T = R_x(\alpha_{i-1}) D_x(\alpha_{i-1}) R_z(\theta_i) D_z(d_i) $$

Where R_x and R_z are the rotation matrices about X and Z axes respectively and D_x and D_z are the translation matrices about X and Z axes respectively. The final DH transformation matrix after multiplication is as follows:

$$ {}^{i-1}_{\ i}T = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) & 0 & a_{i-1} \\ \sin(\theta_i)\cos(\alpha_{i-1}) & \cos(\theta_i)\cos(\alpha_{i-1}) & -\sin(\alpha_{i-1}) & -\sin(\alpha_{i-1})\,d_i \\ \sin(\theta_i)\sin(\alpha_{i-1}) & \cos(\theta_i)\sin(\alpha_{i-1}) & \cos(\alpha_{i-1}) & \cos(\alpha_{i-1})\,d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

This matrix is applied for transformation into adjacent frames and for transformation into n^{th} frame with respect to the root frame, the following multiplication is done,

$$ {}^{0}_{n}T = {}^{0}_{1}T \times {}^{1}_{2}T \times \ldots\ldots\ldots \times {}^{n-1}_{\ \ n}T $$

4.4 Visualization Goals and Challenges

The main target of this research is to aid the therapists in providing therapeutic interventions to the stroke patients for arm rehabilitation. The visualization of mapping of the data on the visual interface is crucial as the accuracy of the therapy depends largely on it. For satisfactory visual assistance, the related goals and challenges in achieving those are mentioned as follows:

- **Modelling of human arm**
  The human arm needs to be properly modeled, preferably as close to real life human arm as possible. This will enable the patient as well as the care giver understand if the position and orientation of the virtual human arm and that of the patient match. This will also guide the care giver to perform the therapy accurately.
  The main challenge in this step is to ensure proper visual representation of the human arm developed using graphic designing tools.
- **Reducing lag between action and representation**
  The time between the data input from the sensors due to motion of the patient's arm, processing the data and visually representing it needs to be reduced as much as possible to ensure greater accuracy of therapeutic intervention and better user experience.
  The main challenge in this step is to ensure compatibility between the graphic design tool and the control program to reduce lag between the arm motion of the patient and visual representation. Greater lag will result in reduced user experience and reduce accuracy of the therapeutic intervention.
- **Correct Mapping of Arm Procedure**
  The orientation and the position of the patient's arm needs to be properly depicted in order to get an idea of how accurately the therapy is being conducted and also to gain knowledge about the patient's improvements in moving his/her arm**.**

The main challenge in this step is to ensure that the real life orientation of the patient's arm and the visual representation of it using the sensor data are almost similar i.e. the error between real life and virtual position and orientation is minimum.

- **Axis Alignment**

  The axes of rotation and motion should be properly mapped to remove any sort of confusion in identifying the arm posture.

  To ensure this the sensor data should be noise free. Applying filters to the sensor data can reduce this noise. Calculating the angular offsets of individual axis in rest position is also necessary to align the virtual arm with the axes perfectly by adjusting the offsets with the data from the sensors.

Chapter 5

Experimental Setup

The experimental setup of this research contains the IMU, processing unit, flex sensor and a PC. At present the visualization is done in MATLAB at the most basic level where the human arm is represented by a combination of lines and the orientation in 3D - space is determined by applying DH transformation. Data related to different arm postures of the therapeutic interventions are obtained from the device and corresponding visual representation is obtained along with the angles made with the axes of rotation. Snapshots of the visual representations are presented at the end of this section.

5.1 Device Description

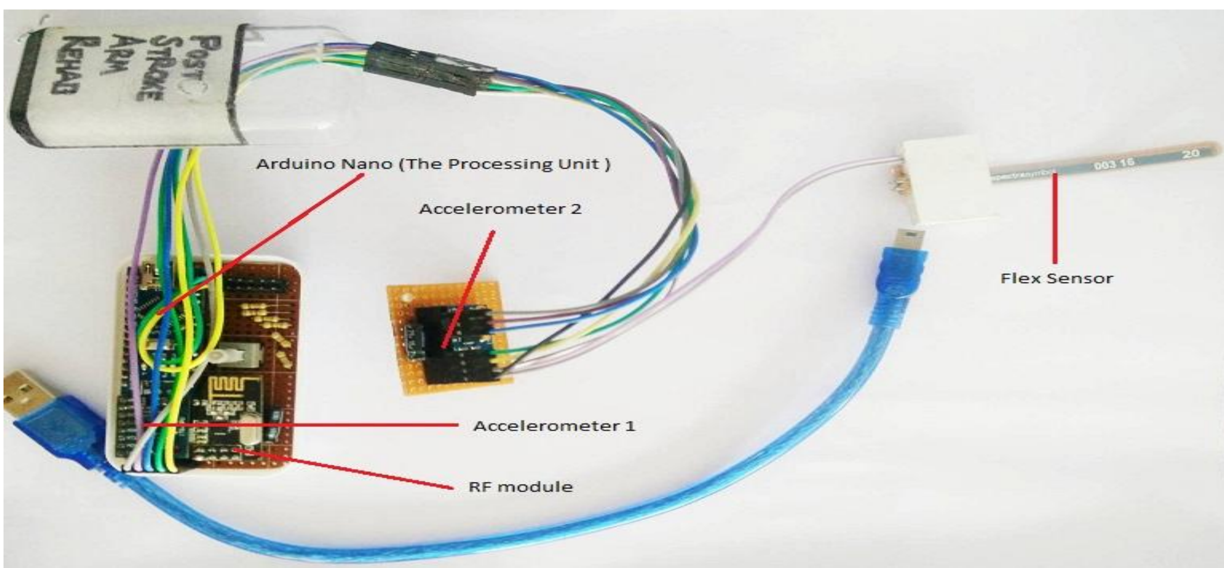


Figure 11: Experimental Setup of the proposed System

The IMU used for our research is the MPU 6050. IMU sensors usually consist of two or more parts. Listing them by priority, they are the accelerometer, gyroscope, magnetometer, and altimeter. The MPU 6050 is a 6 DOF (Degrees of Freedom) or a six-axis IMU sensor, which means that it gives six values as output. Three values from the accelerometer and three from the gyroscope. The MPU 6050 is a sensor based on MEMS (Micro Electro Mechanical Systems) technology. Both the accelerometer and the gyroscope are embedded inside a single chip. This chip uses I2C (Inter-Integrated Circuit) protocol for communication.

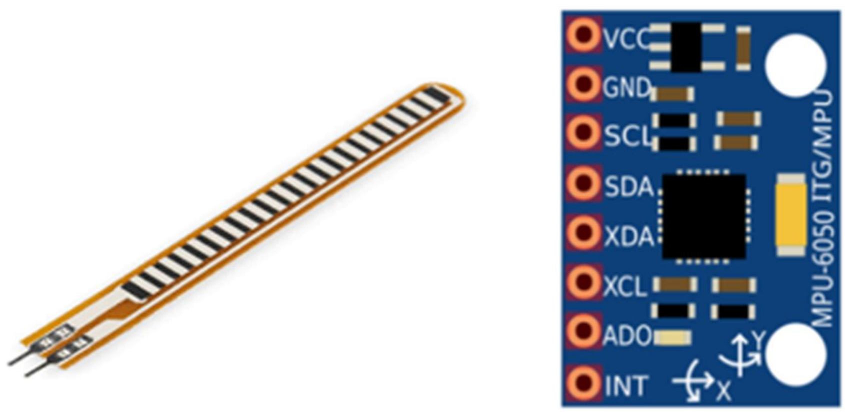


Figure 12: Flex Sensor and MPU 6050

The Flex Sensor patented technology is based on resistive carbon elements. As a variable printed resistor, the Flex Sensor achieves great form-factor on a thin flexible substrate. When the substrate is bent, the sensor produces a resistance output correlated to the bend.

They are usually in the form of a thin strip from 1”-5” long that vary in resistance range. It is obvious that longer strip would give more number of different resistances on bending. The change in resistance with increasing bend is depicted in the figure- 13:

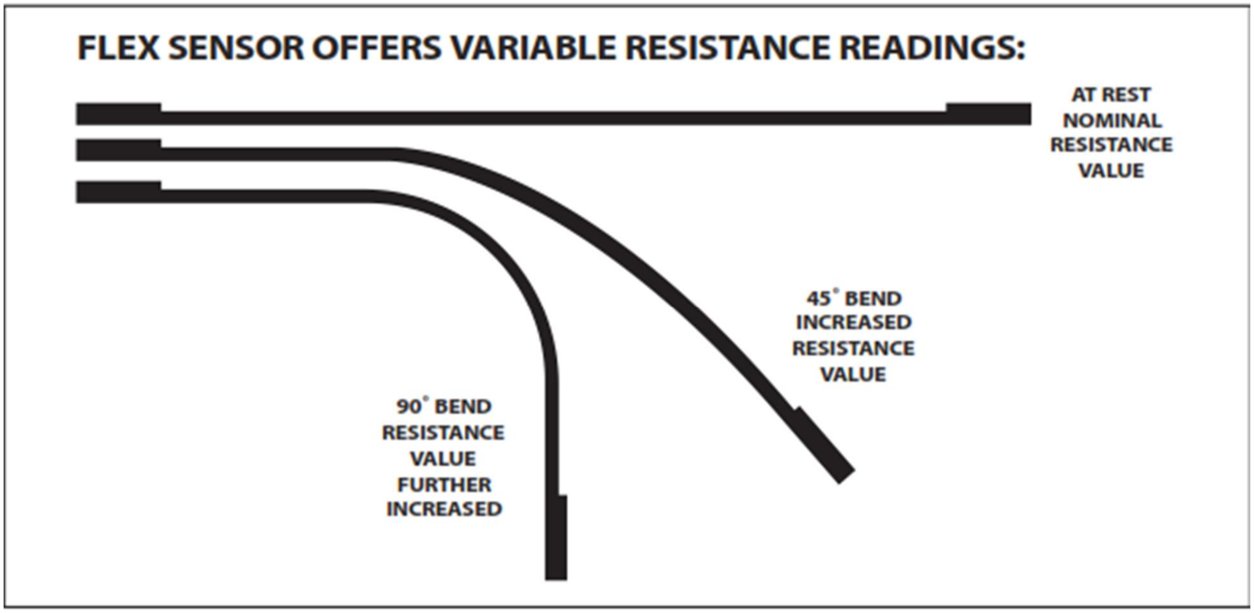


Figure 13: Flex Sensor Bend and Corresponding Angle

5.2 Interfacing Sensors with Arduino

Sensors can be connected with the main mother board Arduino in two sequential ways. First we have to connect the IMUs (Inertial Measurement Units), then we have to connect the flex sensors.

- **Connecting the IMUs**

  The MPU 6050 is connected to Arduino as shown in the following diagram. If the MPU 6050 module has a 5V pin, then it can be connected to Arduino's 5V pin. If not, it will have to be connected to the 3.3V pin. Next, the GND of the Arduino is connected to the GND of the MPU 6050. The sketch used to extract data from the MPU, also takes advantage of the Arduino's interrupt pin. Arduino's digital pin 2 (interrupt pin 0) is connected to the pin labeled as INT on the MPU 6050. Next, in order to set up the I2C lines, the pin labeled SDA on the MPU 6050 is connected to the Arduino's analog pin 4 (SDA) and the pin labeled as SCL on the MPU 6050 is connected to the Arduino's analog pin 5 (SCL). The connections are same for Arduino Uno and Nano.

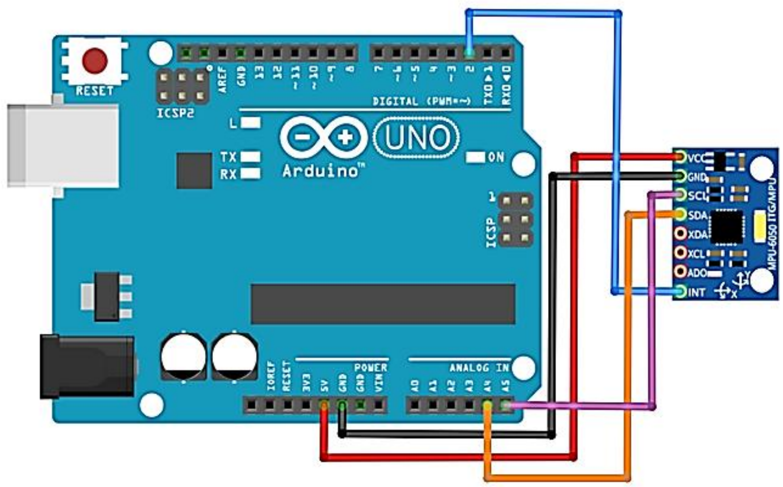


Figure 14: Arduino Connection with MPU

- **Connecting the Flex Sensors**

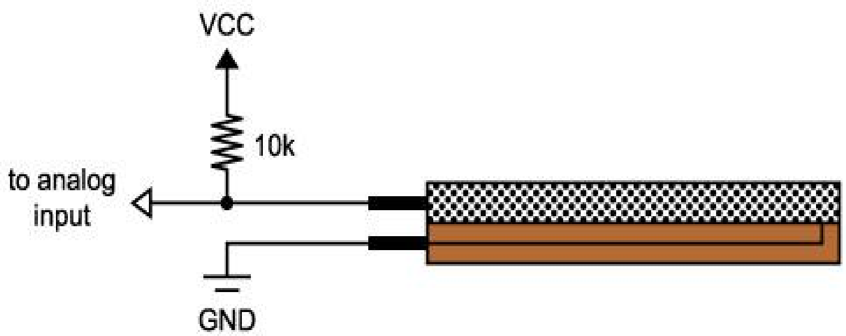


Figure 15: Flex sensor schematic

'Flex Sensor' or 'Bend Sensor' is a sensor that changes its resistance depending on the amount of bend on the sensor. They convert the change in bend into electrical resistance the more the bend, the more the resistance value. Usually a flex sensor is used in voltage divider configuration. It is shown in the Figure -15.

5.3 Experimental Procedure

The total process starting from the data collection from the sensors, processing them and visually mapping them is described as follows:

I. The entry point of the data from the sensors is the Arduino. The data from the IMU is communicated to the Arduino over the I2C protocol and the data from the flex sensor is passed on to the Analog pin A0 of the Arduino.

II. After the data is received the Arduino sends the data over to the PC via Serial interface at a baud rate of 38400.

III. The processing and visualization is currently done using MATLAB in 3D – graphical space.

IV. The data received is passed through the complementary filter described above for preventing drift of the gyroscope data.

V. Then the DH matrix is formed and DH transformation is performed on the received data and the co-ordinates of the joints are extracted i.e. the reference frame origins are generated.

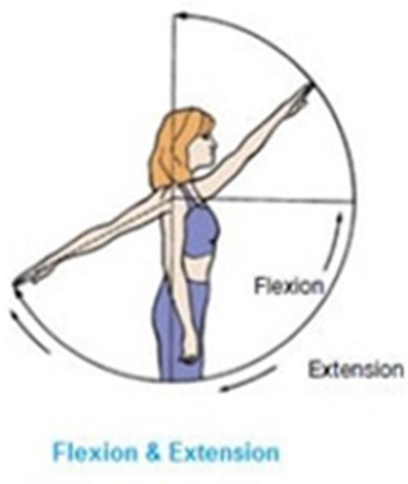
VI. These origins are necessary to draw the lines in 3D – graph in order to visualize the arm postures.

VII. Thus by rotating the IMU and bending the flex sensor we can visualize the arm posture of the patient.

Chapter 6

Experimental Results and Evaluation

The results of different arm postures and their mapping in MATLAB are depicted in the following figures.



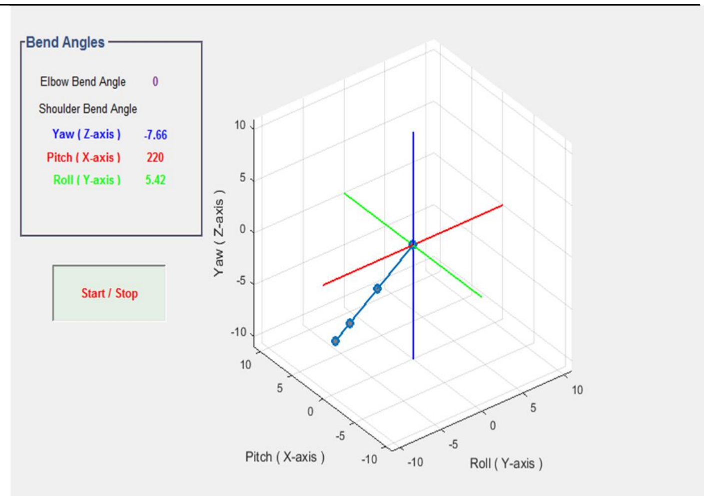


Figure 16: Shoulder Extension arm straight

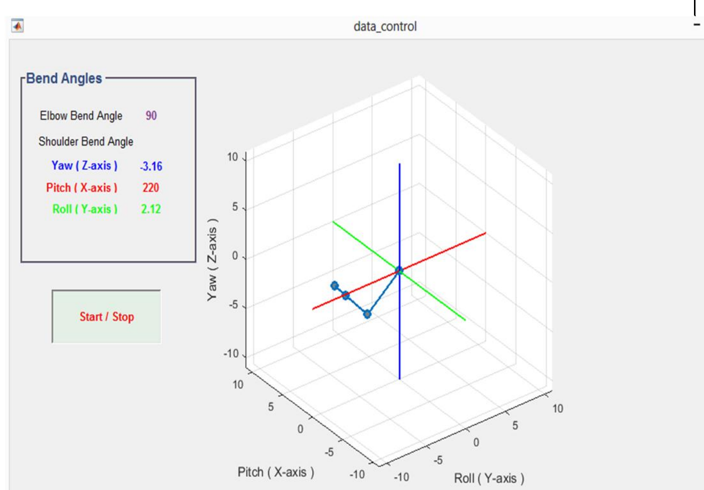
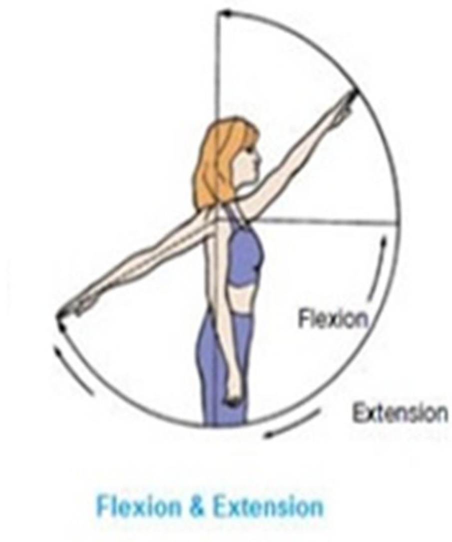


Figure 17: Shoulder extension arm at 90 degree



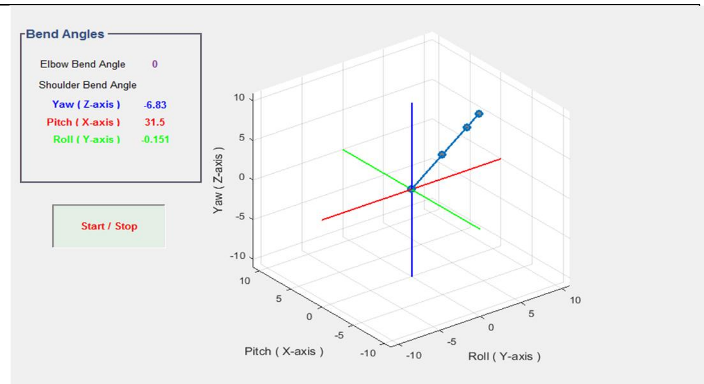


Figure 18: Shoulder Flexion arm straight

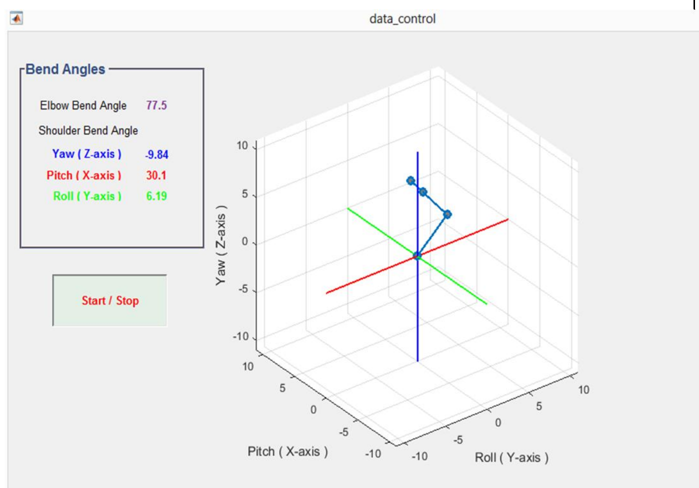


Figure 19: Shoulder Flexion arm bent at 90 degree

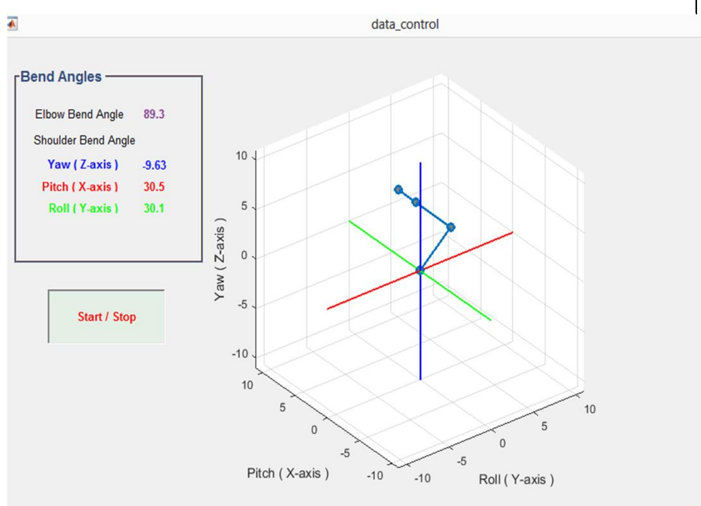
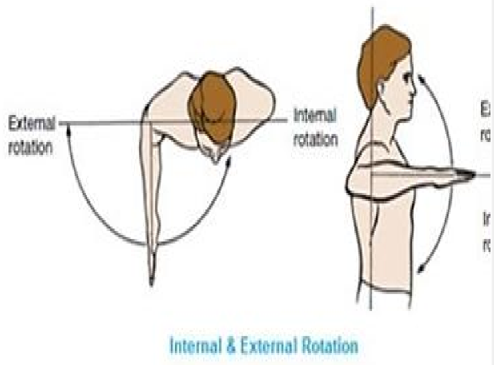


Figure 20 : Flexed Arm Rotated by 30 Elbow Flexed at 90 degree



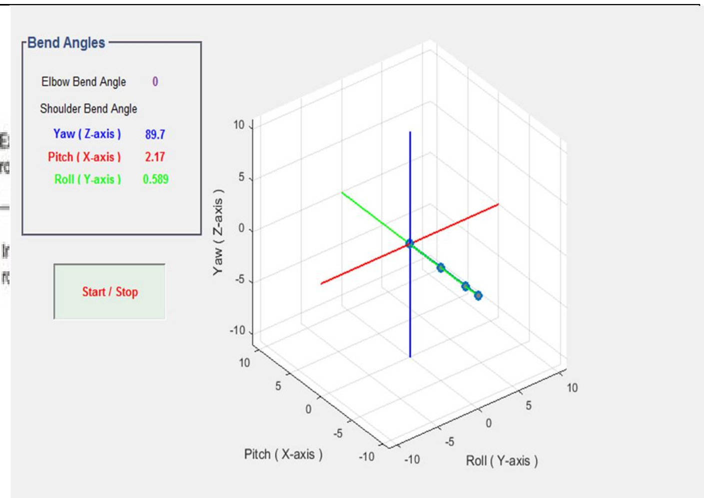


Figure 21: External Rotation Arm Straight

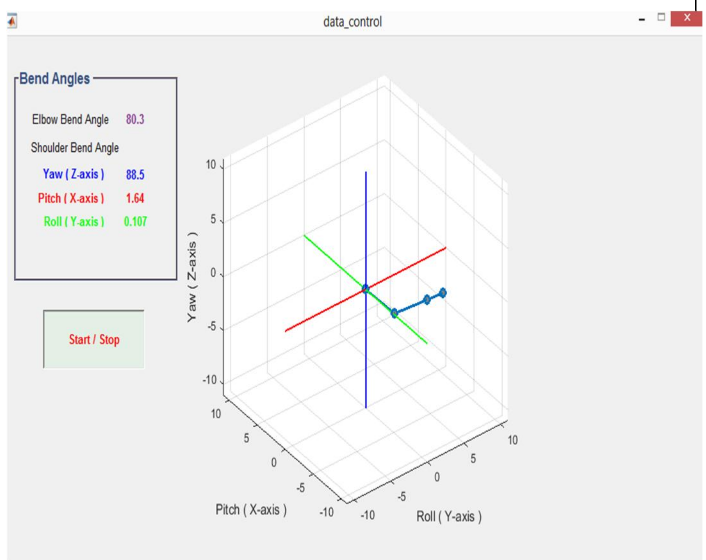


Figure 22: External Rotation Elbow Flexed at 90 degree

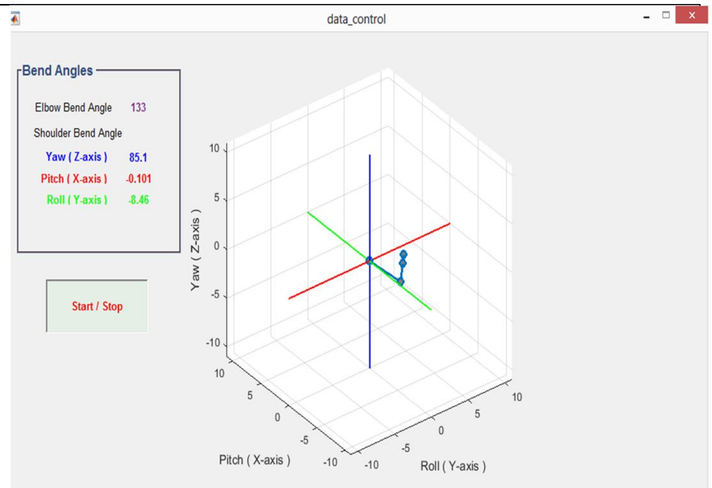
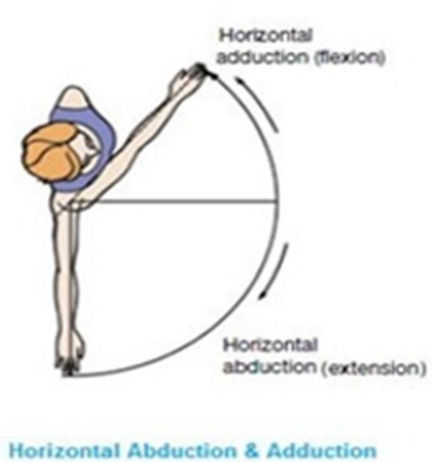


Figure 23: External Rotation Elbow Flexed at 90 degree and Arm Rotated at 90



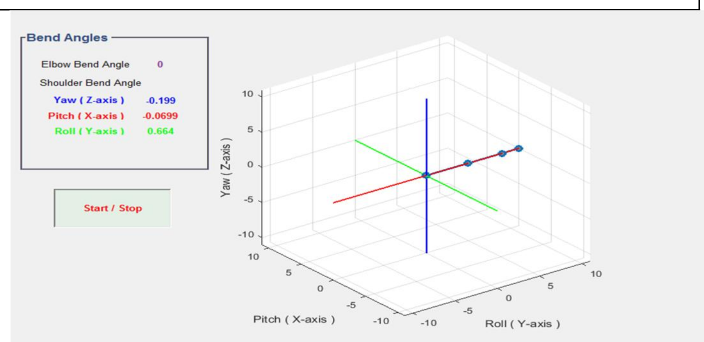


Figure 24: Rest Position

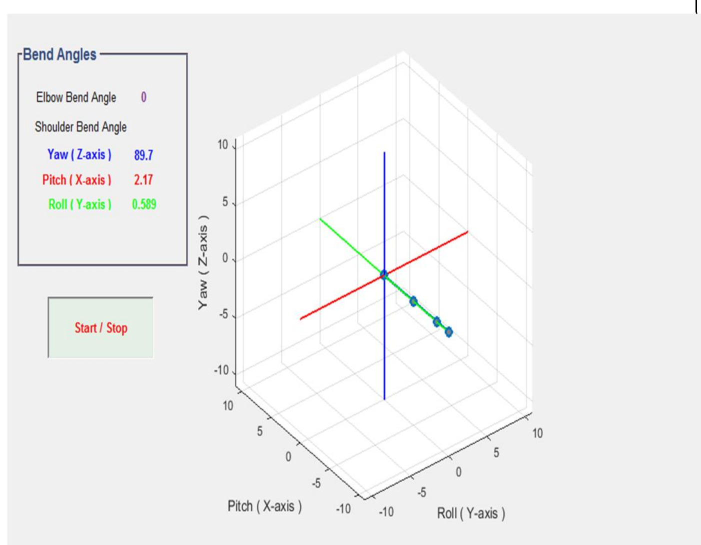


Figure 25: Horizontal Abduction

6.1 Result Analysis

Success behind our research lies in the accurate mapping of arm posture. The experimental results obtained the simulation of the field study conclude-

- The system is capable of generating near accurate position of human arm.
- As it has been possible to map six therapeutic interventions, with more sensors we can map more interventions.
- The process involves simple hardware.
- The readings of the sensors are not consistent.
- Range of movements vary from person to person, so it is not possible to set any standard for measurement without the therapist.
- Each patient's improvement has to be measured based on their previous performance.
- To get consistent readings, high end sensors has to be integrated.

6.2 Evaluation

We evaluated our device with the help of some open minded and enthusiast people. They gave their evaluation on our device based on some categories like- System and real world coincident, User control Flexibility, Design and Accuracy. All the evaluation is not done on real patients who has post stroke arm problems; some are. The evaluation report is given here-

Categories	U1	U2	U3	U4	U5	U6	U7	Average (Out of 10)
System and real world coincident	8	5	6	7	8	8	7	7
User Control	7	6	3	4	7	6	6	5.6
Flexibility	4	5	3	3	4	5	4	4
Design	10	5	9	8	9	8	7	8
Accuracy	10	7	8	9	10	9	8	8.7

Table 4: Evaluation Result Table

If we put these evaluation data in a bar diagram, it would look something like this-

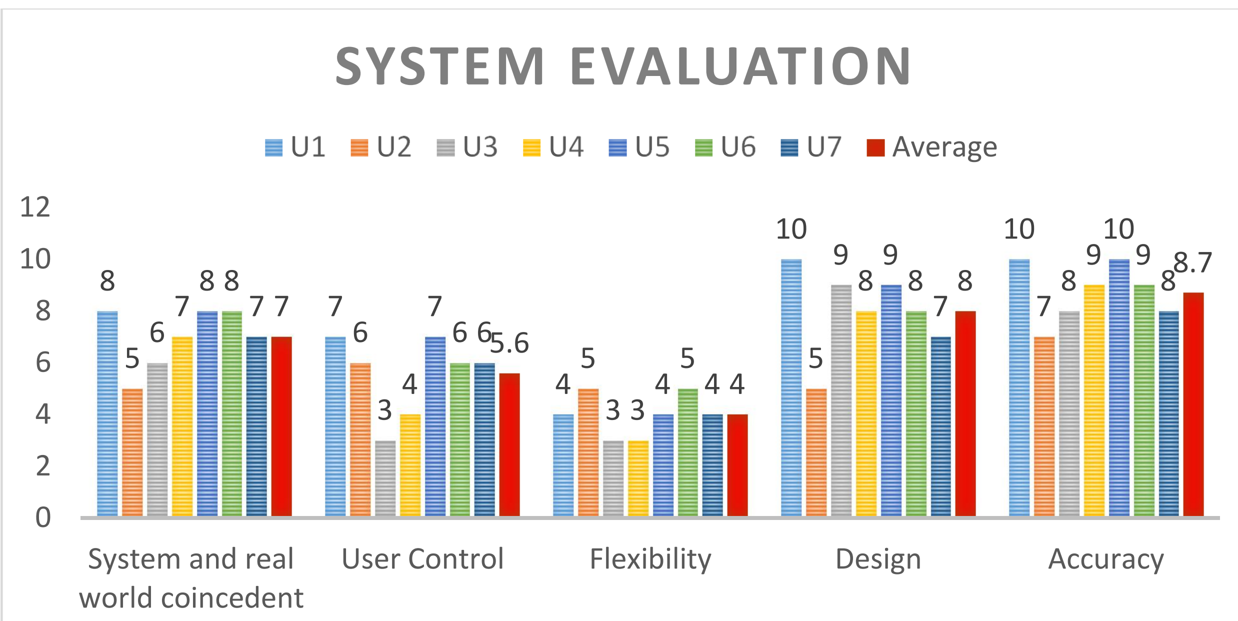


Figure 26: System Evaluation Bar Diagram

The X axis represents the categories and the Y axis represents the evaluated value given by the evaluators. If we study this data thoroughly we can see that we lack effort in Flexibility and User Control; these categories have average value of 4 and 5.6 respectively. We designed the device as a prototype, so there was very little effort to make the device user friendly and flexible.

But we aim to make the device much more fun to use and user friendly at the same time make the device much more flexible for both the patient and therapist.

Chapter 7

Conclusion and Future Works

This dissertation presents a promising human motion analysis tool that can potentially improve current medical approaches in continuous monitoring and tracking a subject's motor motions and limb movements. This system has no limits to the implement environment and to the subjects. At current state, the system can get different arm, shoulder movement reading and map them in a visual interface. Both patients and elder person whose motor functions are needed to be concerned and investigated are available for wearing the system. Despite of those, more work is needed for further validating the performance of developed system. The future works are listed as follows:

- Making the whole system wireless so that the patient can exercise and move their body with ease.
- Applying flex sensors at arm muscle to determine the muscle strength.
- At present the system does not possess a way to track the wrist and finger movements. Applying IMU and flex sensors in wrist and fingers will help to track the movements of the fingers and the wrist.
- Creating a 3D based human arm model which follows the axis alignment and arm posture mapping procedures as the main visual interface.

7.1 Interface Design

The interface we want to implement in the future will look something like this-

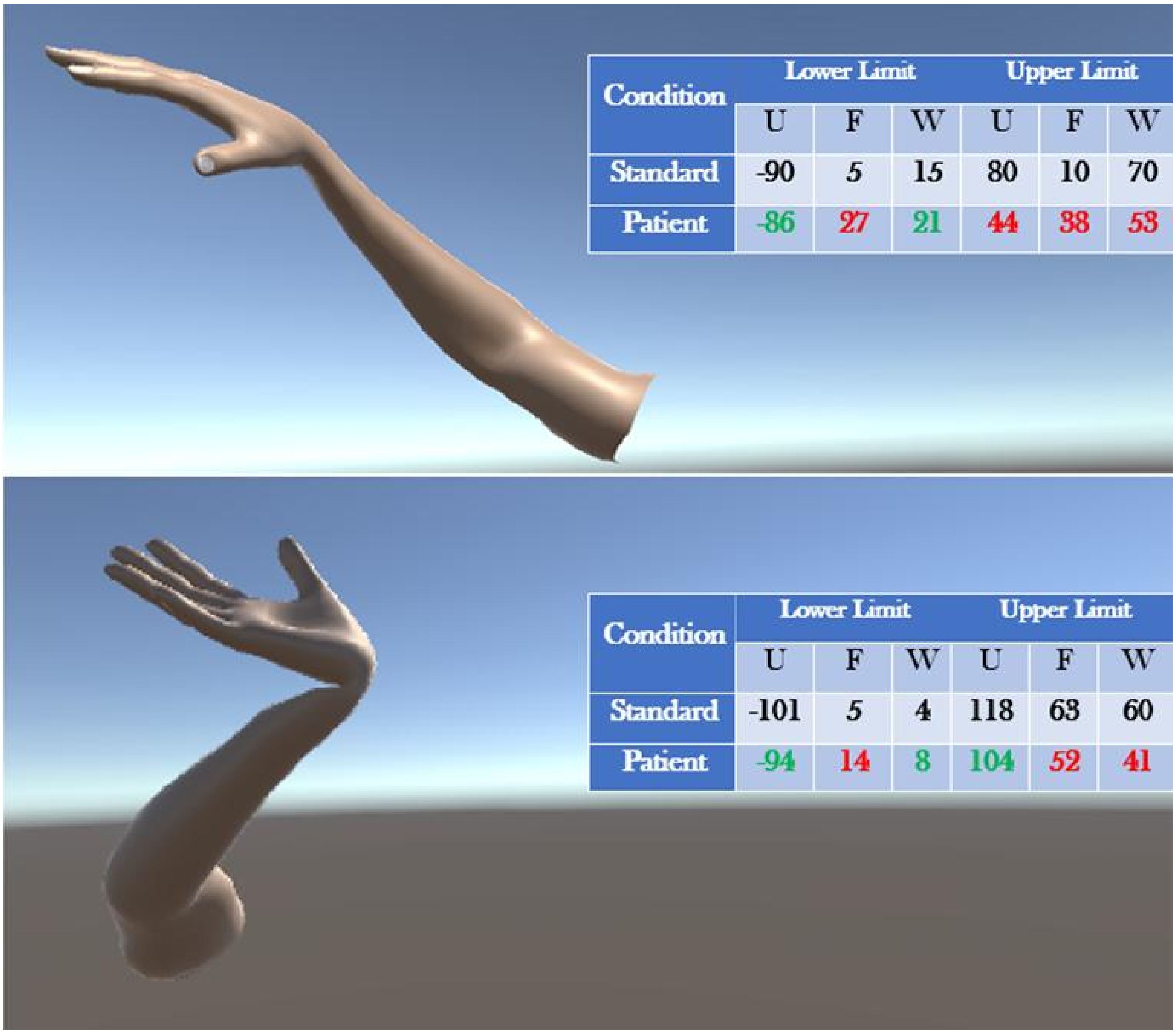


Figure 27: Comparison of arm movement with normal condition and patient condition

Here,

U = Upper Arm.

F=Forearm

W=Wrist

This figure shows the general interface of the device working with the 3D arm model.

The value in red means the difference between the standard person movement condition and the patient’s movement are too big. The value in green means the variation between standard person movement condition and the patient’s movement condition falls in the normal range. But this normal range for variance differs for upper arm, forearm and wrist from person to person; because length of upper arm, forearm and wrist is not same for every person.

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