Department of Electronics & Instrumentation Engineering

A Project Report on

Machine Learning based Automated Knee Physiotherapy Machine

Submitted in partial fulfillment of the requirements for the award of the degree of

Bachelor of Engineering

in

Electronics & Instrumentation Engineering

By

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June 2021

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CERTIFICATE

This is to certify that the dissertation work entitled **"Machine Learning based Automated Knee Physiotherapy Machine."** is carried out by Mr. Vasuki Venkatesh (1MS17EI065), a bona fide student of **Ramaiah Institute of Technology, Bengaluru** in partial fulfillment of the requirements for the award of the degree Batcheler of Engineering **in Electronics and Instrumentation Engineering** of Visvesvaraya Technological University, Belagavi during the year **2020-21**. It is certified that all corrections/suggestions indicated for Internal Assessment have been incorporated in the report deposited in the department library. The project report has been approved as it satisfies the academic requirements in respect of project work prescribed for the said degree.

Internal Guide	**Head of the Department**
(Dr. M.K Pushpa)	**(Dr. M.K Pushpa)**

Name of Examiners: **Signature with Date**

1.

2.

DECLARATION

I hereby declare that the project work entitled "Machine Learning based Automated Knee Physiotherapy Machine." has been carried out by us under the supervision of Dr. M.K Pushpa, Associate Professor and Head, Department of Electronics and Instrumentation Engineering, Bengaluru and submitted in partial fulfillment of the requirements of the award of Batcheler of Engineering **in Electronics and Instrumentation Engineering,** of Ramaiah Institute of Technology, autonomous institute affiliated to Visvesvaraya Technological University, Belagavi during the academic year 2020-21.

This work has not been submitted in part or full for the award of any other degree/ diploma in this university or any other university.

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ACKNOWLEDGEMENT

The gratification of happiness that accompanies any successful work would be incomplete without the mention of the people who made it possible.

We express gratitude to the Head of Department, our guide and the project coordinator **Dr. M.K Pushpa**, Associate Professor, Department of Electronics and Instrumentation Engineering, for providing active support and guidance at every stage of my project.

We thank **Dr. N. V. R. Naidu**, **Principal and Management of MSRIT** Bengaluru for all the support to carry out the project.

We are also thankful to the entire **Electronics and Instrumentation Engineering Department** and my friends for playing an important role in the completion.

We express sincere thanks to my **family** for providing me with all the amenities required to complete the project and being my inspiration throughout.

We wish to thank Dr. Phaneesh M S for providing us the right base, helping us understand the structure of the knee and throwing light on the current technologies involved in treatments and surgeries.

ABSTRACT

As per a report published in Business Standard, there are about 180 million Indians suffering from Arthritis. Studies show that ailments like Osteo Arthritis (OA) of the Knee and Knee related injuries cause chronic pain and stiffness to the knee joint. This affects the range of motion of the leg. The severity of this is highly dependent on the age and BMI (Body-mass Index) of the patient. Patients diagnosed with these knee ailments inevitably should undergo Physiotherapy. With a majority of the demography affected by such ailment, affordability of Physiotherapy becomes a concern. The cost of commuting to the clinic and the fee of the Physiotherapist puts a financial burden on patients. The Continuous Passive Motion machines are also used to provide passive physiotherapy to the patient. These machines are commonly used in hospitals and are generally bulky and expensive and require the intervention of skilled personnel, making the therapy a tedious process.

Thus, we propose an alternative to the existing CPMs; a cost-effective system capable of diagnosing the severity of the knee using machine learning models and provide appropriate Automated physiotherapy. The system can also be utilized for patients who have recovered from stroke or are in a state of coma. The system acquires a set of data from a gyroscopic sensor and through a questionnaire presented in the Graphical user interface. Using a one-dimensional Convolutional Neural network and K-means clustering on the obtained data, an appropriate physiotherapy routine is set for the user in the proposed system.

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CHAPTER 1: INTRODUCTION

INTRODUCTION

Around the world, millions of people suffer from some or the other kind of knee ailments, some that are serious while some that may be a niggle or sorts. A survey that was conducted helped us deduce that over 180 million people suffer from Arthritis and the numbers are increasing by the day and thus, it's a matter of great concern to both the fields of medicine as well as technology.

The number of sports injuries are increasing due to the emphasis on sports as a catalyst to child development and we, as a generation have seen how sports can become a career choice, unlike before. But, with the advent of such modern thinking and rigorous training comes the problem of injuries. These injuries, if not taken care of properly during the initial stages can cause problems as serious as ending a person's entire career. Thus, treatment and physiotherapy are imperative in these situations.

Furthermore, due to the increasing population as well as improper roads and negligent driving, there has been a huge spike in the number of road accidents. Also, through a detailed survey it was found that in most of the accidents that include a pedestrian and a vehicle, the pedestrian's knee takes the first impact and thus, pedestrians are always at risk of such injuries. There are other causes of knee injuries that include Diabetes, chronic disease and aging.

Most of the knee injuries that call for surgeries, as is the case as mentioned above, need a well-defined course of physiotherapy and treatment and thus, increase cost and requirement of skilled personnel. Also, in cases of Comatose patients and patients who have recovered from Stroke, they lose mobility in the lower limbs and thus, they need a passive motion exercise to bring back the lost mobility.

As per a detailed survey and discussion with doctors, it was found that the single most effective exercise for knee ailment was providing it mobility so as to strengthen the muscles that surround the patella and thus increase the overall strength of the knee.

Thus, keeping the above-mentioned requirements, a problem statement was defined. The basic idea of the project is to make a low-cost physiotherapy machine for the knee that can help save time as well as money. We also aim to provide a mobile system that can be deployed and set up easily and thus make the process of recovery more comfortable and faster.

1.1 LITERATUREREVIEW

Knee ailments can potentially range from genetic disorders to accidental injuries. Initial diagnosis of any problem of the knee is solely based on the extent of the mobility of the knee. Age, Sex, BMI are further taken into account to obtain accurate inference in the process of diagnosis. Recovery of the knee joint post-diagnosis predominantly depends on systematic physiotherapy. Age, joint injury, obesity, genetics, and anatomical factors that affect joint mechanics and therefore considered vital factors in determining the severity of Osteo Arthritis or stiffness in the joint. The most commonly affected joint in the body due to

Osteoarthritis (OA) is the knee, in particular, the strength due to weight of the body, gait, and flexibility of the joint was reduced by 43.8% in people suffering from OA [1]. Extensive research clarifies that knee rigidity is associated with stereotypical knee-stiffening gait pattern which reports instability in motion and balance which is proportional to age in 68% of the cases [2]. Physiotherapy is broadly classified into Active Physiotherapy and passive physiotherapy. Active Physiotherapy is when the patient can provide therapy by putting effort on their own to move their muscles. Passive physiotherapy is carried out manually with the appointed Physiotherapist or by utilizing a Continuous Passive Motion (CPM) machine. The greater the flexion angle of a knee, the healthier the knee. An experimental study infers that patient suffering from knee ailments can extend or flex their legs, ranging from 0 to 60 degrees. Such motion produces an optimum result without damaging the tissues near the joint and over-stressing the muscles with excessive therapy [3]. Continuous manual physiotherapy over 4 weeks has a positive impact on reducing pain, increasing range of motion and functionality of the knee, this helps us understand that creating an automated physiotherapy routine that emulates the medically accepted passive physiotherapy will largely help the people affected be independent and control their therapy [4]. Post-surgery patients and aged patients with affected knee are generally prescribed to undergo Passive physiotherapy. CPMs are used to rehabilitate the range of motion for post-operated Knee by providing passive physiotherapy. These devices consist of large mechanical changeable parts to adjust for different patients. These usually make the them very bulky. Therefore, CPMs are generally are used in the hospitals. Furthermore, the CPMs used in the hospitals are quite expensive which adds on to the financial burden for patients to obtain the therapy. The proposed system is comparatively cheaper and removes the requirement for the patient to travel to the hospital due to the device's portability. As shown in the Fig. 1, the device consists of minimal moving parts, making it simpler to use on a day-to-day basis. Using gyroscopic sensors, the system is capable of providing initial condition of the knee by quantifying the severity of the affected knee using One-Dimensional Convolutional Neural networks (1-D CNN). This quantified severity of the knee is termed as Knee Quality metric (KQM). Further, with other details of the user and the obtained KQM, the proposed system is capable of determine the right predefined Therapy routine for the user using K-means clustering algorithm and execute automated passive physiotherapy. While the Existing CPMs consists accurate feedback system to set defined cycles of physiotherapy, making them a simple closed loop systems to automated physiotherapy. The proposed system takes a step further in integrating Artificial Intelligent methods to determine the range of motion of the user and provide corresponding physiotherapy. The existing state of the art technologies using Deep neural network and predictive analysis to determine the quality of the affected knee due to various Knee ailment use their input parameter as either medical Images like X-RAY or MRI images and Gait Pattern analytics. Although these methods effectively determine the quality of the knee, obtaining these parameters require use of expensive resources. The proposed system collects simple gyroscopic gait pattern with simpler yet effective use of gyroscopic sensor setup. Further, the architecture of the proposed algorithm is computationally inexpensive and faster in determining the quality of the knee. According to a report published by Business Standard, a study conducted by SRL diagnostics revealed that 180 million people in India suffer from Arthritis. Due to the increase in population and thus, an increase in vehicular movement, the number of road accidents has been increasing lately. An exponential increase in sports injuries has been observed lately. Constant tension on the knee patella leads to severe knee injuries in sportspersons [5]. Most of these knee ailments require a timely intervention in the form of Physiotherapy to make sure the injury does not aggravate Such physiotherapy improves the range of motion of the knee [6]. Angular velocity and range of motion of the knee are drastically reduced for people who have generative Osteo-Arthritis. Extensive passive motion and muscle strengthening to the knee for these patients increase the rate of improvement of the knee range of motion and angular velocity of the knee [7][8]. Furthermore, it is advised to the post-surgery patients to exercise their Knee by Passive motion using medical elastic bands or Continuous Passive Motion machines [9]. In [10], the impact of physiotherapy after knee surgery is observed. The study was done on 50 patients who had undergone Anterior Cruciate Ligament Reconstruction surgery and were subjected to physiotherapy after for a period of 12 months. It was observed that the group that underwent the therapy had a better recovery of knee and lead a better quality of life. [11] observes the rehabilitation of the knee after a meniscus repair. Here too, it was observed that patients that underwent physiotherapy after surgery had a faster recovery of range of motion than the ones that didn't. [12] conducted an extensive research experiment on how physiotherapy would help relieve the pain caused by OA. The patient was a 52-year-old male with pains in both knee joints while walking and standing. After undergoing physiotherapy for a certain period of time, it was observed that the pain felt by the patient had significantly reduced. Apart from manual therapy done by clinical staff, there exists a Continuous Passive Motion (CPM) Machine that can automate the process of physiotherapy. In the paper CPM Machine Protocol for Knee Replacements [13], the standardized processes for the usage of CPMs was observed after a Knee Replacement surgery. The patients were given two hours of therapy every day for a period of six weeks. [14] observes the usage of CPMs for therapy as compared to manual therapy. Forty patients who had undergone Knee Arthroplasty were chosen at random and divided into two groups. One group would be subjected to normal physiotherapy whereas the other would be using the CPMs. Both groups underwent their respective regimens for the stipulated period of time. At the end of the experiment, it was observed that the Range of Motion of patients who were subjected to therapy by the CPMs was around 7.2 degrees more than the other group. [15] An adaptive haptic interaction architecture for knee rehabilitation robot was designed which essentially was a complex closed loop system. This system allowed the CPM to provide Passive Movement or Active movement based on the condition of the Patient. The system is capable of adjusting speed and threshold angle based on inputs given by the Doctor or Surgeon. Though, the system is not independent of a Medical Professional supervision, it is designed with great consideration of several parameters when treating patients with physiotherapy. [16] Another study conducted an experiment to predict the pain in the knee and existence of OA in elderly women by Gait Analysis. 18 elderly women were asked to enroll in the experiment, the test patients were asked to climb a set of stairs and their Gait Pattern was recorded. Using Support Vector machines, the pain was predicted with an accuracy of 83% and existence of OA was detected with an accuracy of 97%. This was solely done by analyzing gait pattern of the patients. [17,18] determine extremely effective method to detect severity of the knee to classify knee OA using DenseNet CNN algorithm and Siamese CNN algorithm respectively. The output of both proposed methods was compared with True Kellgren and Lawrence (KL) grading to obtain the model accuracy. The overall accuracy of the model was 77% and 86% respectively. [19] determines not one but two different ways to determine the severity of the knee affected by OA using Radiological Imaging and Gait Pattern analysis. The results with the Deep CNN Inception-RESNET model with Radiological images was 87.6% and the accuracy using the gait pattern was 88.6%

1.2 OBJECTIVES

- To automate the process of physiotherapy.
- To deliver a much-needed product for physiotherapy that can be used at home.
- To reduce the cost of treatment.
- To increase the efficiency of the treatment and cut down on the recovery time.
- To get the quality of a licensed physiotherapist in a portable machine.

1.3 ORGANIZATION OF THE REPORT

This report gives a basic description about how we are going to implement our project and the literature survey included here gives us an idea on how to implement various innovations and overcome the problems that are faced in the development process.

In order to provide an easier understanding of the following project it has been organized into the particular categories. Following are the categories:

- Chapter 1: It includes the basic idea behind selecting the project, literature survey, objectives and scope of work.
- Chapter 2: It consists of basic introduction to the project and the basic block diagram of the overall system.
- Chapter 3: It explains the hardware and software sections with implementation details.
- Chapter 4: It explains about the results obtained from the existing model of the project.
- Chapter 5: This chapter has the conclusion of the project.

CHAPTER 2: METHODOLOGY

METHODOLOGY

2.1 SUB-SYSTEM EXPLANTION:

2.1.1 MPU6050 GYROSCOPE

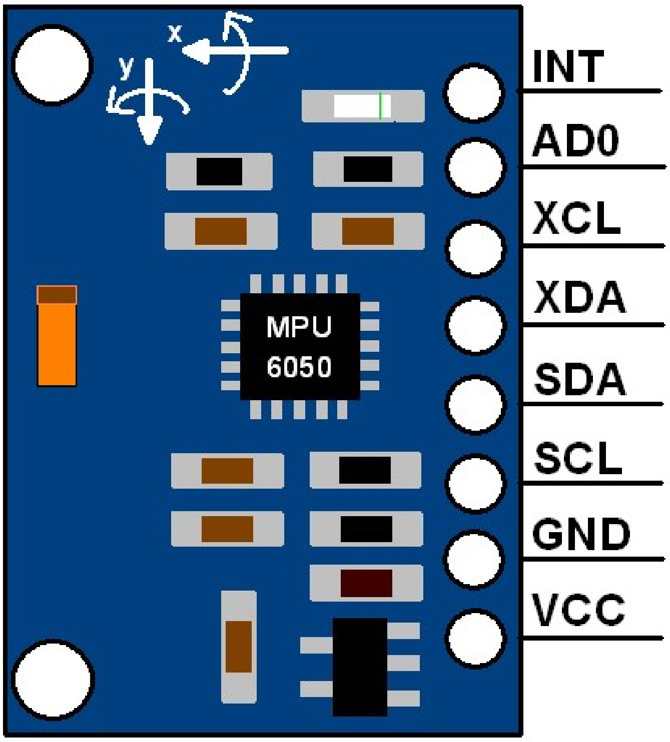


Figure-2.2- MPU6050 Module

This sensor comprises a complete 6-axis motion tracking device. It’s a combination of 3-axis Gyroscope and 3-axis accelerometer. It also a has a small package of Digital Motion Processor to detect the motion when its being used. It also comprises of an on-chip Temperature sensor as an added advantage in case we want to upgrade new features into the system.

The MPU6050 consist of 3-axis Gyroscope with Micro Electro Mechanical System (MEMS) technology. It is used to detect rotational velocity along the X, Y, Z axes as shown in below figure.

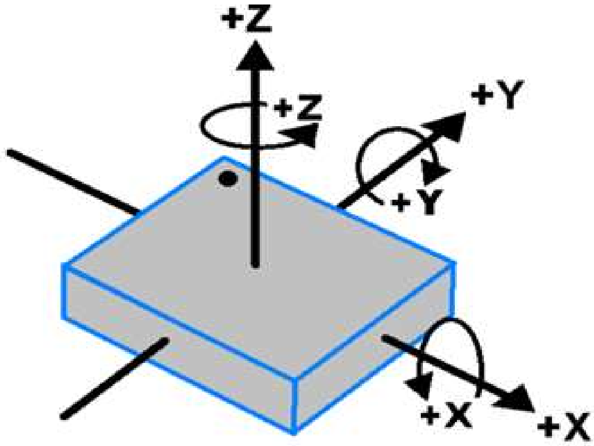


Figure-2.3- MPU6050 Orientation and Polarity of rotation

Working:

i. Coriolis effect takes place when the gyros are rotated about any of the sense axes which causes a vibration that is detected by the MEM placed inside MPU6050.
ii. The resulting signal is amplified, demodulated, and filtered to produce a voltage that is proportional to the angular rate.
iii. This voltage is digitized using 16-bit ADC to sample each axis.
iv. The full-scale range of output are +/- 250, +/- 500, +/- 1000, +/- 2000.
v. It measures the angular velocity along each axis in degree per second unit.
vi. In the proposed system, MPU6050 senses change is Euler angle along the Y-axis. The read angle is communicated to the Microcontroller via I2C communication protocol.

2.1.2 LINEAR ACTUATOR:

Linear Actuator is a hi-tech electric device capable of converting rotational motion from low voltage DC motors into linear push/pull movement. Produces a translatory motion.

i. Motor: The linear actuator being used is a 12V DC motor that interacts with other parts of the actuator to deliver linear movement. It comprises of an important component called the limit switch.
ii. Limit Switch: the motion of this device is controlled by this switch. When it is triggered, movement comes to a halt.
iii. DC Brushes: their main purpose is to convey the current between the stationary wires which is responsible for bringing current into the actuators.
iv. Lead Screws: their main purpose is to convert the rotational motion into linear motion.

v. Gears: they are the intermediate component that connects the lead screw which facilitates the free movement.
vi. Cylinders: the cylinder does not move as such but the parts inside it do move in an oscillatory to and fro motion.

Working*:*

Electric Linear Actuator consists of two main components a gear box that provides rotary motion with the help of dc motor and a lead screw to provides the linear motion. The electric motors rotation drives the primary gear of the gearbox, which through single or multiple gear stages turns the gearboxes output shaft (final gear). This rotates in unison with the lead screw. When the lead screw rotates the lead nut that mates with the lead screw translates along the screw and so converts rotary motion to linear motion.

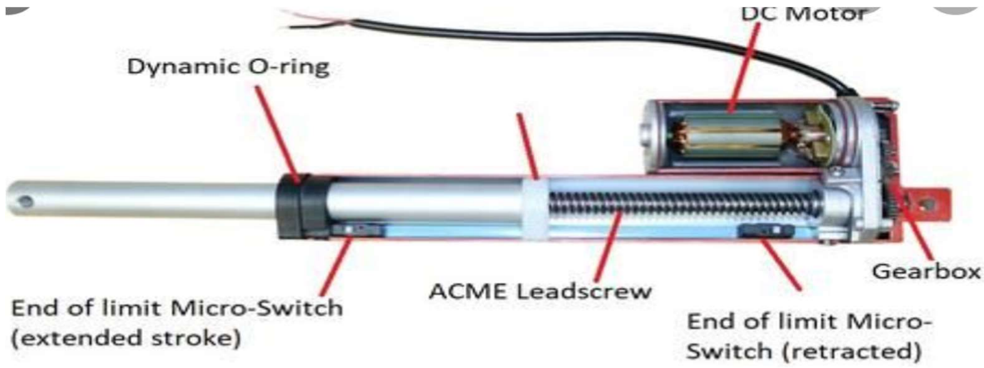


Figure-2.4- Linear Actuator

2.1.3 ESP32 Microcontroller:

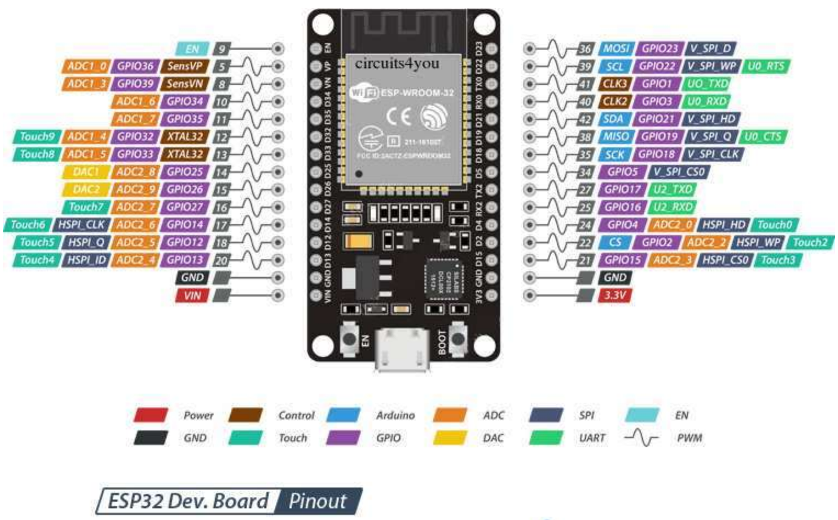


Figure-2.6- ESP32 Microcontroller

i. ESP32 is a microcontroller that was designed by Espressif Systems. It is preferred due to its compact size, flexibility in usage and due to its wide range of applications. It is used for applications that include, Embedded systems, Automation, Instrumentation etc.
ii. An inbuilt Bluetooth module is present in the ESP32 Dev board which was utilized for the project.
iii. The Microcontroller is capable of establishing I2C, SPI, USART/UART communication protocols to read various sensor values.

2.1.5. IBT-2 MOTOR DRIVER:

The motor driver IC is used as a switching device to change the direction of supply current to the load. Changing the direction of current changes, the direction of rotation. The circuit uses four capacitors to compensate for any voltage fluctuation and thus does not fry the IC.

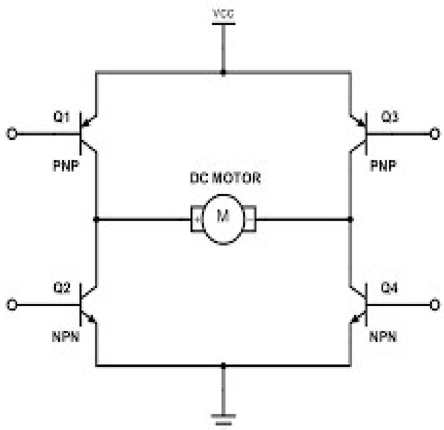


Figure- 2.7(a)- H Bridge Figure-2.7(b)- IBT-2 Motor Driver

Working:

The IBT-2 module uses a H-bridge to reverse the direction of current to the motor. From figure 6a, the circuit can be referred. It consists of a pair of NPN transistors and a pair of PNP transistors. It also consists of the motor in the middle, forming a H like structure and thus, the name, H-bridge. At a time, the diagonally opposite NPN and PNP transistors are activated (Q1 and Q4 form a pair and Q2 and Q3 form a pair) and thus, the motor rotates in that direction of flow of current. When Q1 and Q4 are activated, the motor is rotated in the clockwise direction and when Q2 and Q4 are activated, the motor rotates in the anti-clockwise direction.

2.2 HARDWARE INTERFACING:

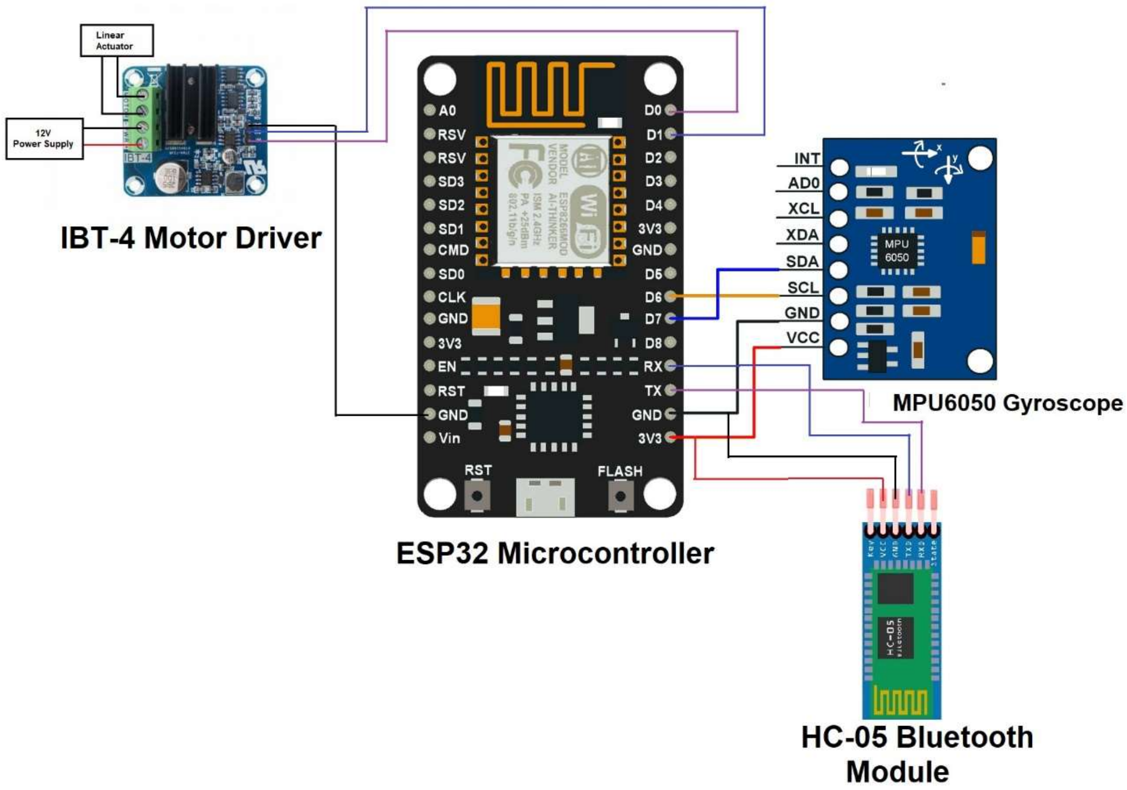


Figure-2.8- Hardware Interfacing Diagram

The main component of the system is the ESP32 Microcontroller. It is the brain of the design. The actuator is controlled by the Motor Driver IBT-4. Two controlling pins of the motor driver are connected to pins 0 and 1 which are the PWM pins of the microcontroller. A common ground connection is made between the Motor driver, the Microcontroller and the other modules. The power supply is connected to the positive and ground of the Motor Driver. The two ends of the Linear Actuator's motor is connected to the two pins of the Motor Driver.

The Gyroscope Sensor MPU6050 is interfaced in a similar way. The VCC and Ground pins are connected to the 3.3V and GND pins on the microcontroller respectively. The SCA and SCL pins are connected to Pins 6 and 7 of the microcontrollers.

The HC-05 Bluetooth Module is also connected to the Microcontroller. The GND and VCC are connected to the GND and 3.3V of the ESP32. RX and TX pins are connected to the TX and RX pins of the Microcontroller respectively.

2.3 SOFTWARE

2.3.1 Python

Python is a high level dynamically typed language used for machine learning, web development, operating systems and application development. with its easy-to-use syntax and vast resource libraries, it provides a way to develop robust applications inclusive of a variety of features.

PyCharm is a dynamic integrated development environment for the python programming language that offers a wide range of features for ease for coding from intelligent code completion to beautification, it allows programmers to develop software code that is clean and precise.

2.3.2 Graphical User Interface

The graphical user interface is a form of user interface that allows users to interact with electronic devices through graphical icons and audio indicator such as primary notation, instead of text-based user interfaces, typed command labels or text navigation. It is a system of interactive visual components for computer software. A **GUI** displays objects that convey information, and represent actions that can be taken by the user. The objects change colour, size, or visibility when the user interacts with them.

Kivy is an opensource multi-platform GUI development library for Python and can run on iOS, Android, Windows, OS X, and GNU/Linux. It helps develop applications that make use of innovative, multi-touch UI. The fundamental idea behind Kivy is to enable the developer to build an app once and use it across all devices, making the code reusable and deployable, allowing for quick and easy interaction design and rapid prototyping.

2.3.3 Machine Learning Algorithm – 1 D CNN using KERAS

Machine learning is a branch of artificial intelligence (AI) and computer science which focuses on the use of data and algorithms to imitate the way that humans learn, gradually improving its accuracy.

Through the use of statistical methods, algorithms are trained to make classifications or predictions, uncovering key insights within data mining projects. These insights subsequently drive decision making within applications and businesses, ideally impacting key growth metrics.

A **Convolutional Neural Network (ConvNet/CNN)** is a Deep Learning algorithm which can take in an input image, assign importance (learnable weights and biases) to various aspects/objects in the image and be able to differentiate one from the other. The pre-processing required in a ConvNet is much lower as compared to other classification algorithms. While in primitive methods filters are hand-engineered, with enough training, ConvNets have the ability to learn these filters/characteristics.

The architecture of a ConvNet is analogous to that of the connectivity pattern of Neurons in the Human Brain and was inspired by the organization of the Visual Cortex. Individual neurons respond to stimuli only in a restricted region of the visual field known as the Receptive Field. A collection of such fields overlaps to cover the entire visual area.

When a large number of features exist in data, the complexity of the data also increases. Typical classification algorithms tend to perform well. Neural networks are best suited to these kinds of complex data frames. A convolutional Neural network uses a trainable filter that performs convolution on the input layer of the network. Features learned by a CNN are more robust compared to a Multi-layered perceptron and chances of model overfitting are significantly reduced.
The convolutional neural network tends to be robust when a change in the input data is observed, like padding, skewing, scaling, etc. This variant of a convolutional neural network requires a smaller number of perimeters and outputs higher accuracy on 1-Dimensional time-variant signals. They are well suited for applications in mobile phones or microcontrollers. Due to convolution, the parameters within the 1-dimensional filters are tightly packed and therefore learn the pattern of the 1-D inputs [5].

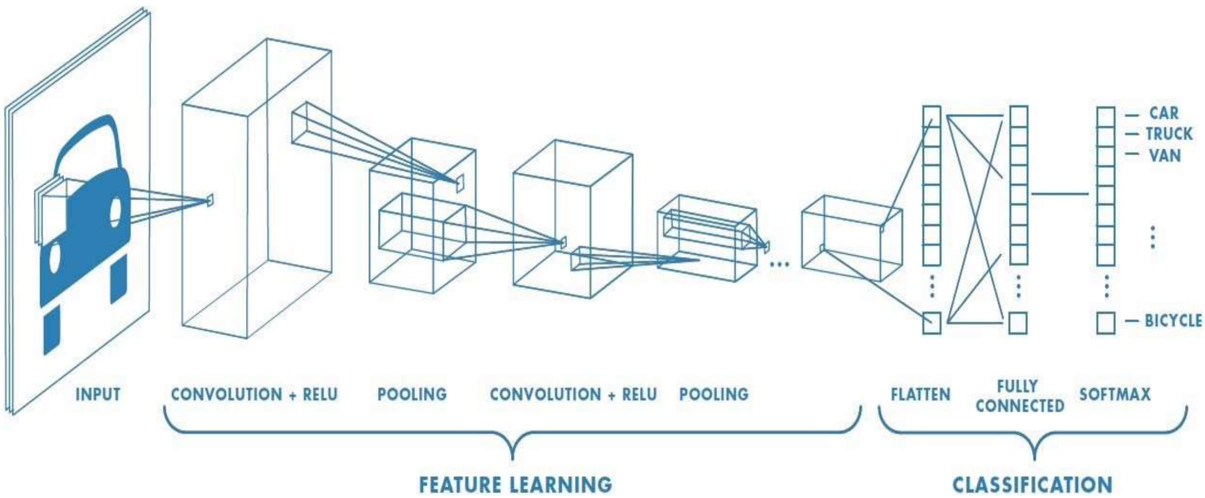


Fig 2.9 Understanding Convolution

About KERAS
Keras is a high-level, deep learning API developed by Google for implementing neural networks. It is written in Python and is used to make the implementation of neural networks easy. It also supports multiple backend neural network computation.

Keras is relatively easy to learn and work with because it provides a python frontend with a high level of abstraction while having the option of multiple back-ends for computation purposes. This makes Keras slower than other deep learning frameworks, but extremely beginner-friendly.

2.3.4 K – Means Clustering using Scikit learning

K-Means is an unsupervised learning algorithm. The algorithm is used to cluster or create partitions in the data based on similarity in features of the samples. This algorithm is capable of accepting input and clustering without a label set [6]. K-Means Clustering method is performed as follows:

i. Determine the number of clusters (denoted by *k*).
ii. Assign *k* number of random points as centroid s.
iii. Calculate the Euclidean distance of all samples from the centroids.
iv. Assign the sample points to the closest centroid.
v. Calculate the mean distance of each assigned point from its respective centroid.
vi. Move centroids such that mean distance is reduced.

Repeat Step 1 to 5

Scikit Learning

It features various classification, regression and clustering algorithms including support vector machines, random forests, gradient boosting, k-means and DBSCAN, and is designed to interoperate with the Python numerical and scientific libraries NumPy and SciPy.

Scikit learn is a python library which is primarily used for machine learning. It is built on existing technologies like NumPy, matplotlib and pandas. It allows us functionality like regression, classification, clustering, model selection and pre-processing.

2.4 SOFTWARE INTERFACING DIAGRAM

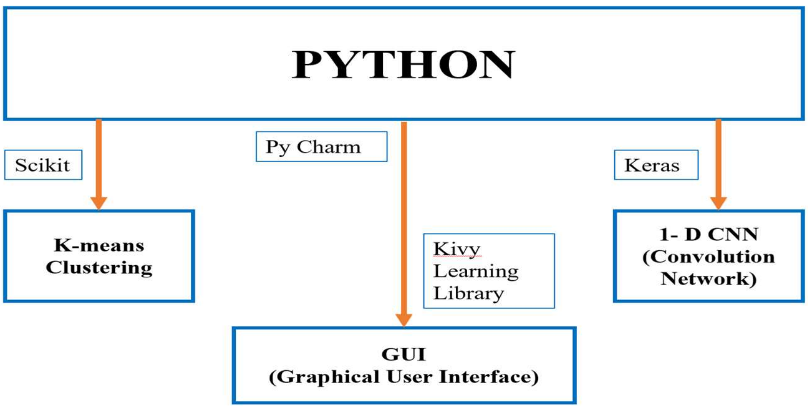


Fig 2.10 Software Interfacing

2.4 BLOCK DIAGRAMS OF THE PROPOSED SYTEM

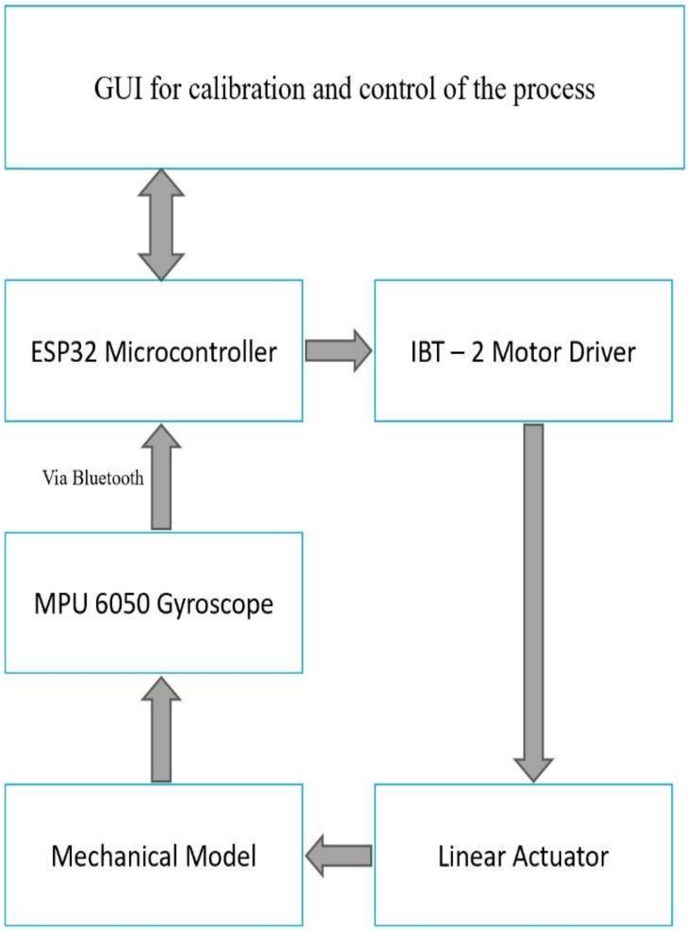


Figure 2.9 Flow Diagram of the System

ESP32 Microcontroller is first initiated with a signal which triggers the IBT – 2 motor driver to start the process, followed by triggering the linear actuator to move the mechanical model. Movement of the mechanical model is along the y-axis. This movement is recorded in the form angles by the MPU 6050 Gyroscope and send this data to the microcontroller via I2C communication as serial data which is stored in the form of an array. The resulting array is transmitted to the GUI via Bluetooth to process the data and devise an automated therapy.

2.5.1 Hardware Flow Chart

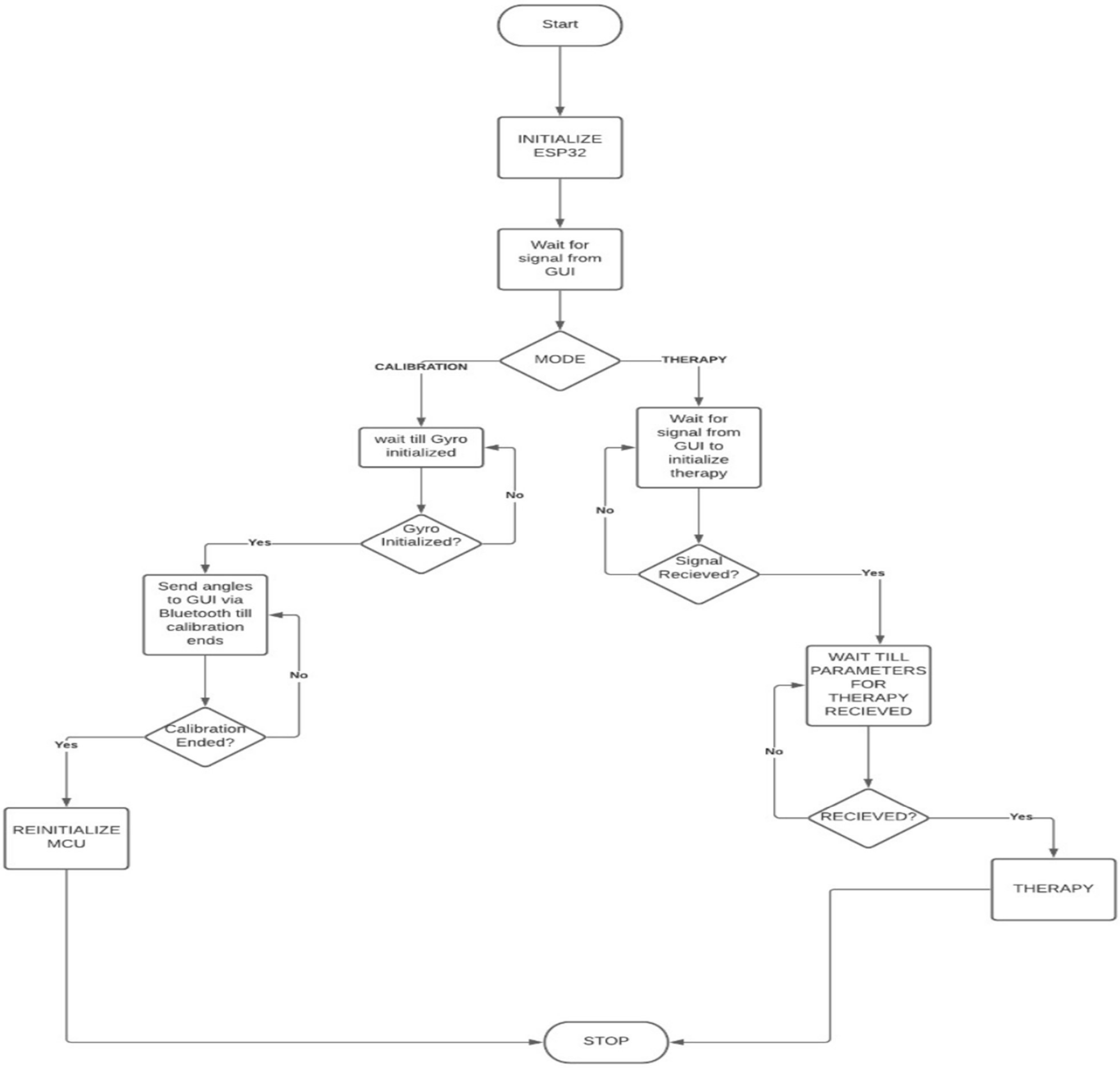
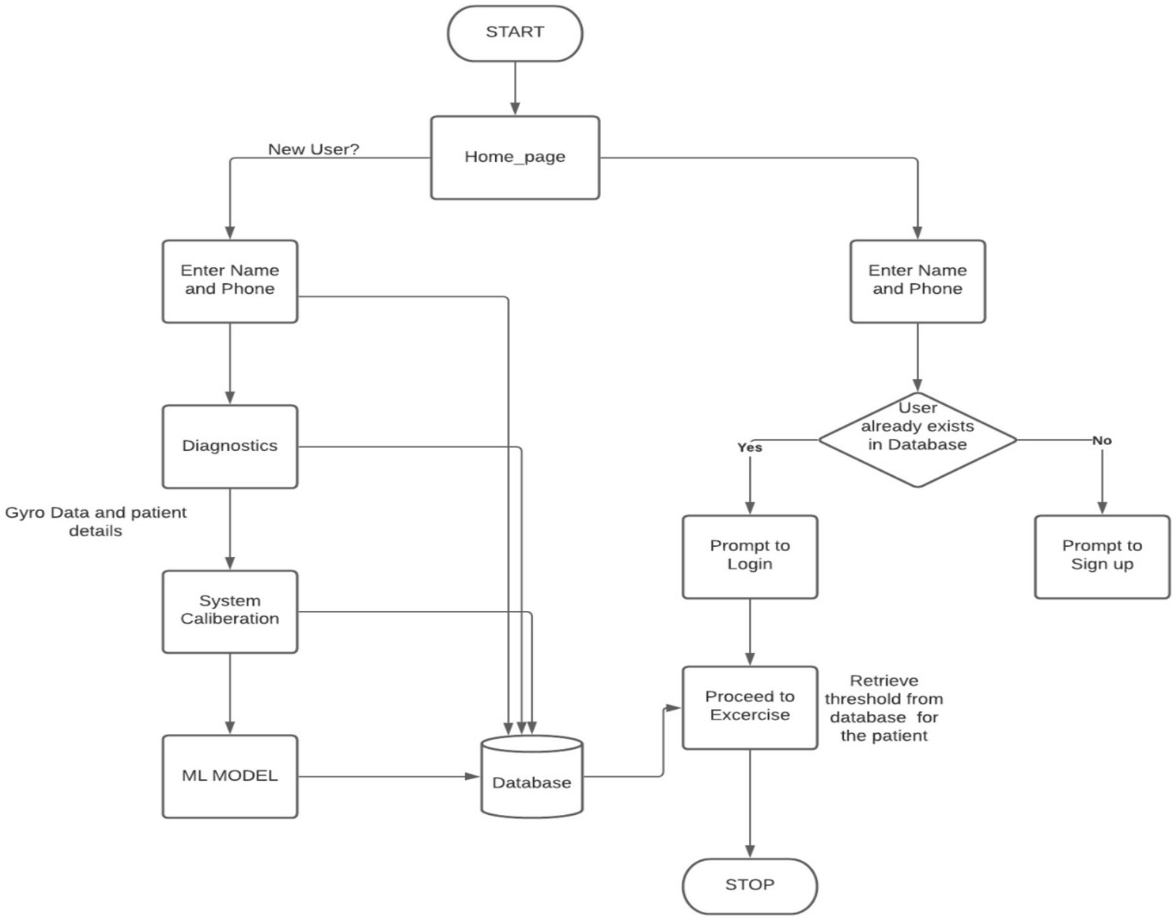


Figure 2.10 Hardware flow chart of the proposed system

2.5.2 GUI Flowchart



CHAPTER 3: IMPLEMENTATION

3.1 EXPERIMENTAL SETUP

The complete design shown in Fig. 1(a) homogeneous gyroscopic data and to execute accurate tests. Two wooden planks – plank A and plank B, are connected by a hinge joint, making an 'L-shaped structure'. The joint supports the leg such that:

i. The thigh rests on plank A
ii. The calf rest on plank B

This wooden structure is further attached to a wooden chair. The rear plane of plank B is attached to a linear actuator to allow flexion and extension of the leg. (Fig. 1a). The Linear actuator has a full load capacity of 200N enabling it to withstand any sudden resistance by the user. It is controlled by an ESP32 microcontroller through an IBT2 motor driver. An MPU-6050 gyroscope sensor is used to collect real-time gyroscopic data. The sensor is placed on the edge of Plank B, very close to the knee to collect accurate real-time Euler-angles made by the movement of the leg (Fig. 1b).

The Bluetooth module in the ESP32 is utilized to control this design by a PC through a Graphical User Interface (GUI). The GUI is used to execute two phases of the system:

i. Calibration Phase – To determine threshold angle and,
ii. Physiotherapy Phase –Automated Therapy

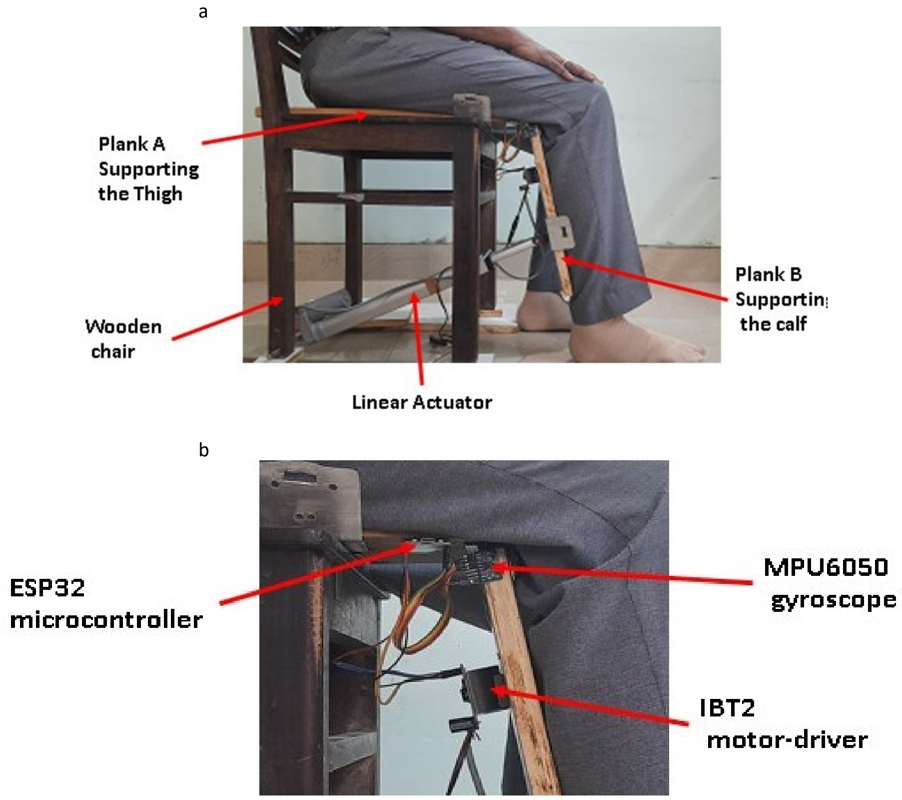


Fig3.1 (a) Complete Design; (b) Magnified at the hinge joint

3.2 Implementation Diagram of Complete System

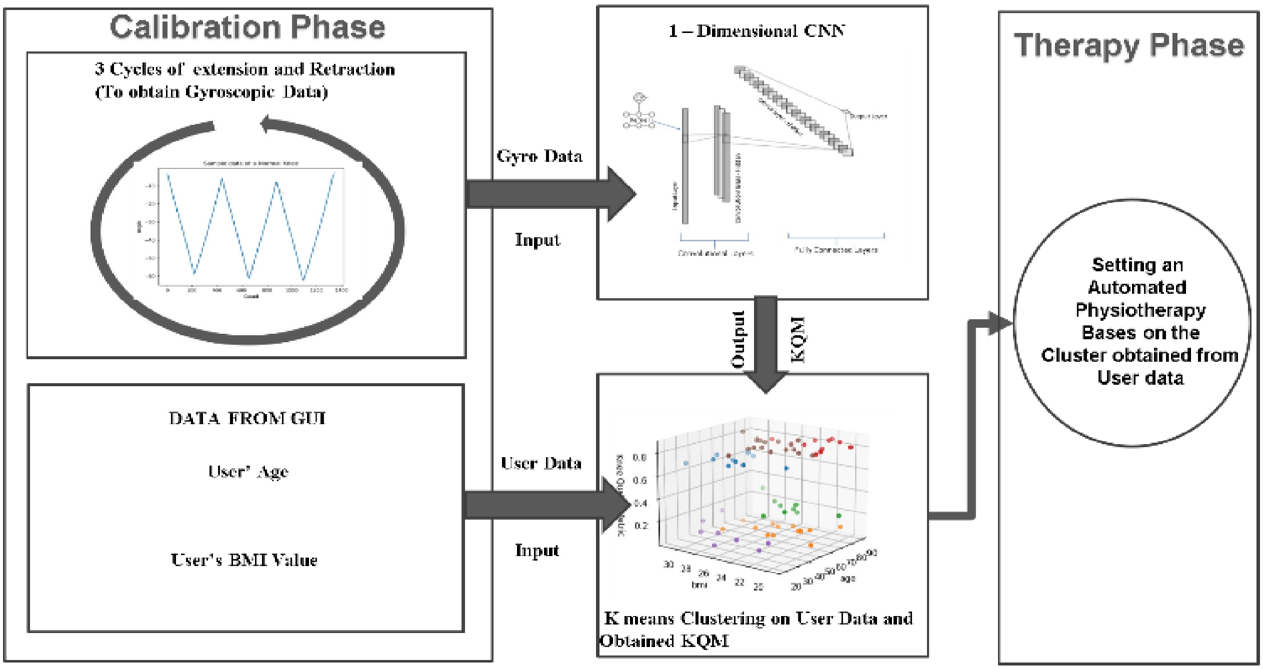


Fig 3.2 Complete Flow Diagram

The complete flow diagram in Fig. 2 is shown in this subsection. Each block of the subsection is explained in detail in the following subsections.

3.3 CALIBRATION PHASE

DATA ACQUISITION

The calibration phase plays a vital role in determining the severity of the user's knee condition. It helps us determine what is the maximum amount of extension the user's leg can make without the user suffering any pain. Initially, the leg is placed and strapped on the 'L-shaped structure'. The user is given complete control; to acquire the gyroscopic data for further analysis. Once the ESP32 microcontroller is connected with the PC, the user can passively flex or extend their leg by controlling the retraction and the extension action of the Linear actuator.

As shown in Fig. 3, first, the user can adjust the initial position of his leg by the *Extend* and the *Retract* button. These buttons allow the user to extend or retract the linear actuator to set the initial position of their leg. In (Fig. 3a), the *Start* button extends the Linear actuator from a fixed position, causing the leg to extend. Therefore, the user can allow the passive extension of their leg till they experience any sort of discomfort. When the user experiences any pain or discomfort, the linear actuator is retracted back to its initial position when the *Stop* button is clicked, as shown in (fig 3b). This cycle of extension and retraction is carried out 3 times.

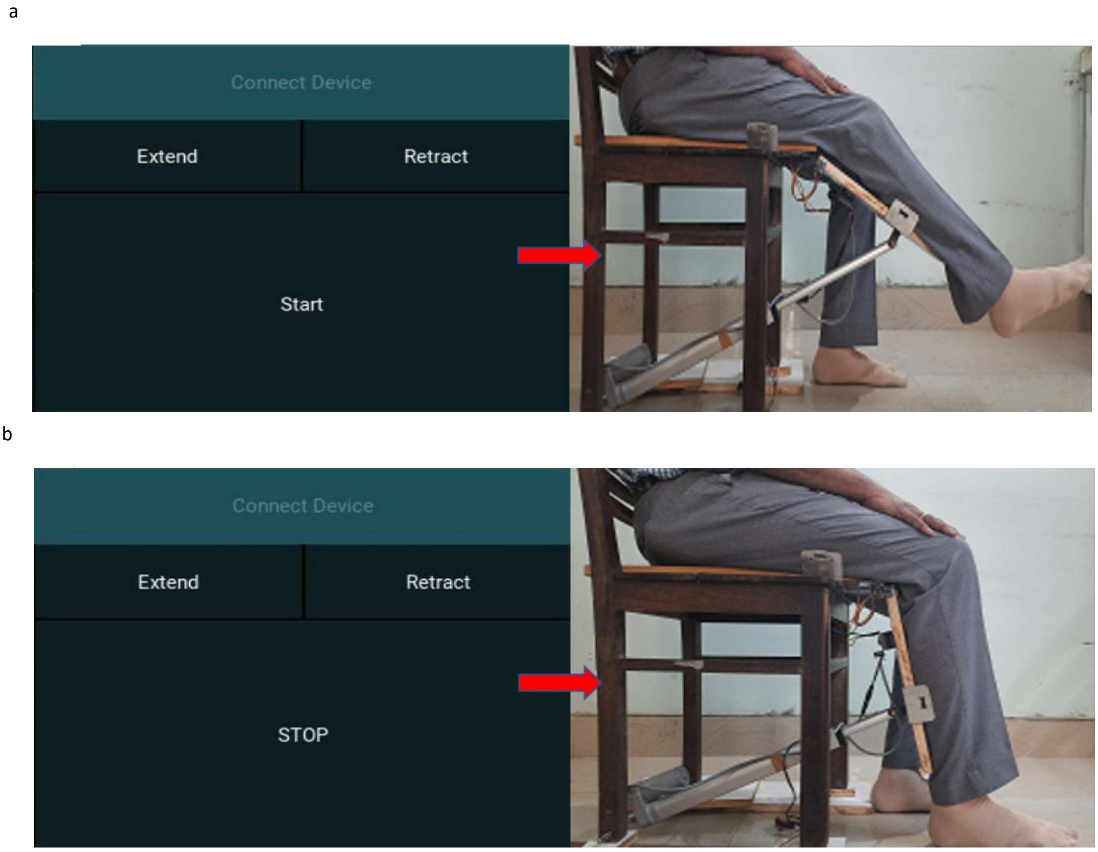


Fig 3.3 (a)Extension of the Leg; (b) Retraction of the Leg

During this process, the MPU6050 gyroscope continuously reads the real-time variation in angles along the direction of the leg movement. Further, the read sensor data is stored in a buffer array, in the ESP32 memory. This data is sent back to the PC once the 3 cycles are finished.

Fig. 4 represents the 1-dimensional array of gyroscopic data during the Calibration Phase. The X-axis denotes the count of the output sensor value and Y-axis denotes the change in Angle. From a set position, as the leg extends, the change in angle observed here is from 0° to -70°. During Retraction, the angle returns to 0° from -70°. (The negative sign here is due to the orientation of the sensor attached)

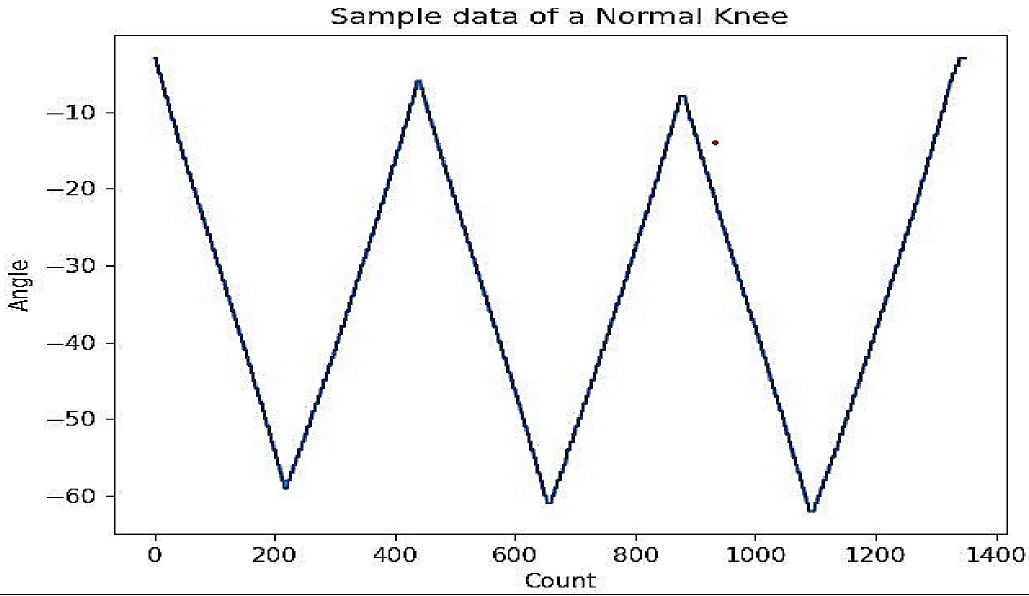


Fig3.4 Sample Gyroscopic Data

Data Pre-processing

The received 1-D gyroscopic array from the microcontroller undergoes two preprocessing phases:

- Sample Thresholding
- Sample Resizing

Sample Thresholding: Since the sensor collects data in real-time, the size of different samples collected varies. A large number of static sensor values are read during the calibration phase. After completion of one Calibration cycle, the user might take time to initiate the next cycle. Between these two cycles, a time delay is observed. During this time delay, the sensor starts reading a static angle value as there is no movement of the leg in this time delay. This results in storing static values in the buffer array.

To overcome this, a limit angle is set. Values that are smaller than this limit angle are only stored in the array and values above the limit angles are discarded. This simple logic ensures no static readings are stored in the array. Fig. 5a depicts before and after sample thresholding.

Sample Resizing: Each sample of the training data must be of a fixed length. To ensure that, sample resizing is done. Sample with the largest array length is determined from the training data. Every other sample is resized to the largest sample size. This is done by repeating the sequence of each sample till the length of each sample is equal to the length of the largest sample. Fig. 5b depicts before and after sample resizing

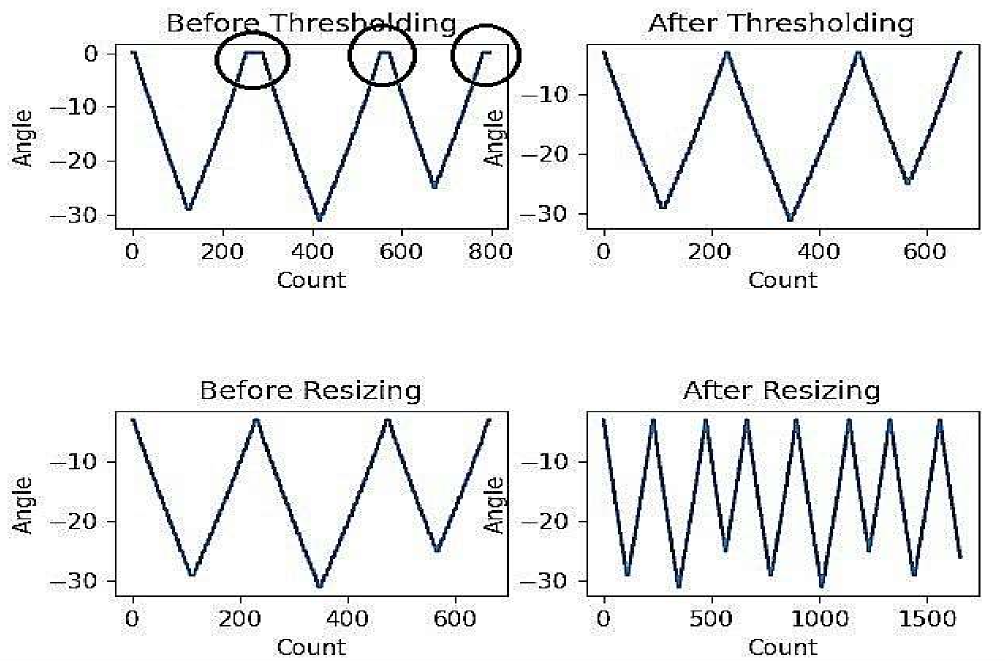


Fig 3.5 Resizing and Thresholding

3.4 The Machine Learning Algorithm

Training Data for the Model

Experimental data was collected by simulating different possible cases to train the 1-D CNN model. A total of 84 samples of different permutations were created which consisted of a 1-D gyroscopic array ranging from 0° to -70° and other features specific to the user were collected through a set of questions that were asked to the user in the GUI (Fig. 4). The following features were collected for the 84 different samples in the training data:

i. Age,
ii. Sex,
iii. Height in meters,
iv. Weight in kilograms,
v. If the user was recently injured in the knee?
vi. If the user underwent surgery on the knee?
vii. 1-D gyroscopic array collected from the MPU6050 sensor

From Height and weight, Body to mass index was calculated from the following formula:

$$BMI = Weight/Height^2 \quad (1)$$

The training data set were labeled as ‘p’ to denote a sample as affected knee, and ‘n’ to denote a sample as a normal knee.

3.4.1 STEP 1: 1D – CONVOLUTIONAL NEURAL NETWORK

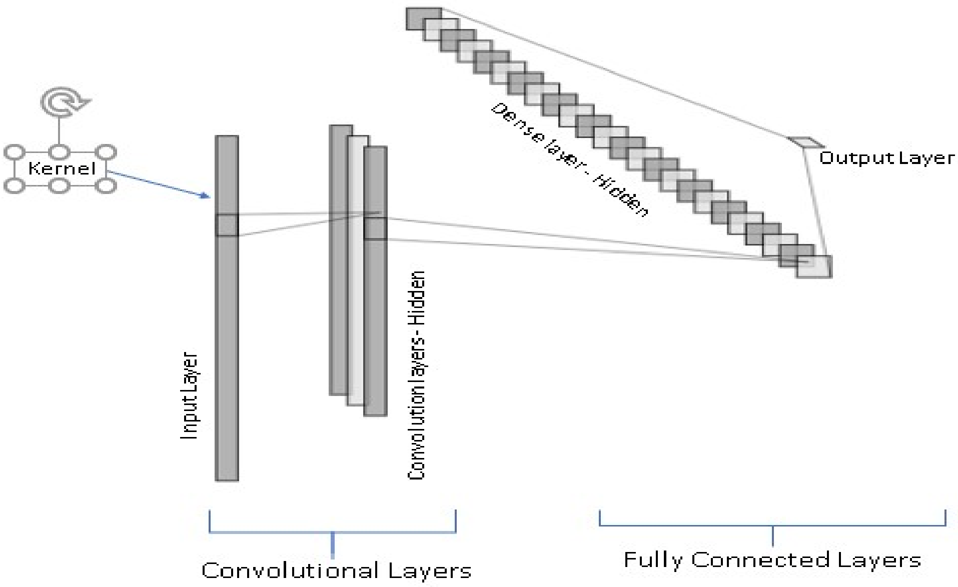


Fig 3.6 One-Dimensional CNN model

In the proposed system, the quality percentage of the knee, termed as the Knee Quality Metric (KQM) was quantified by utilizing a 1-D Convolutional Neural network model. This model was trained on the aforementioned training data using Keras This 1-D CNN model was trained as a linear regression model by using *Linear* activations for the hidden layer and Sigmoid activation for the output layer. The input layer of the 1-D CNN model is the obtained 1-dimensional Gyroscopic array from the sensor. The output layer consists of a single node representing the KQM. Fig. 6 shows the 1-D CNN network. These steps were followed to train the neural network Model:

i. Forward Propagation of 1-D CNN is given in Eq. 2.

$$x_k{}^l = b_k{}^l + \sum_{i=1}^{N_{l-1}} conv1D\left(w_{ik}{}^{l-1}, s_i{}^{l-1}\right) \tag{2}$$

Where, *x is the output obtained when kernel w convolves with the input s.*

l is the current layer and k is the current neuron of the input signal. Here, s is the obtained gyroscopic data obtained after the calibration phase.

ii. The output obtained after performing the convolution pass is fed into the fully connected layers of the neural network where the forward propagation is governed by the eq. 3

$$h^{out} = {h_{i-1}}^{out} \cdot W_i + B_i \tag{3}$$

Here i defines the current layer of the neural network and B is the Bias of the Network. W is the Weights governing between layer i and i-1.

h is the activated neurons of layer i.

iii. The Output layer of the 1D CNN consists of a single neuron which is activated by the sigmoid activation function given in Eq. 4

$$Y = \frac{1}{1+e^{-x}} \tag{4}$$

Where Y is the output of the 1D-CNN and x is the input to the final layer of the network.

iv. Mean Squared error is calculated between the obtained output from the forward propagation and True label of the sample. The Mean squared error is calculated from Eq. 6 as shown

$$MSE = \frac{1}{m-1}\left(\sum_{i=0}^{m}\left(\hat{Y_i} - y_i\right)\right) \tag{5}$$

v. Post obtaining the MSE, backward propagation is carried out to train the 1D – CNN.

Table 1. Sample training data

label	Age	Sex	BMI	Undergone Surgery?	Recent knee injury?	Gyroscope data
n	23	male	25.6	No	No	[0,0, -1, -2...-6, -7...0]
p	67	female	21.3	No	No	[0, 0, -1, -1, -2, -55…]

The model outputs a value between 0 to 1 which essentially regards to the KQM. A value closer to 0 can be inferred as a good knee and vice versa. The following tabular column (Table 2) specifies the parameters of the model.

Table 2. One-Dimensional CNN model Parameters

Model Parameters	Column A (*t*)
Total No. of layers	4
# Hidden layers	2
Output Layer Activation	Sigmoid
Hidden Layer Activation	Linear
Loss	Mean Squared Error (MSE)
Optimizer	ADAM
# Epochs for training	10
Batch Size for training	16

Kernel Size of the Convolutional layer	16
Stride of the convolutional Layer	4
Padding	Same
Filter output from Convolutional layer	3
Total Trainable parameters	75,860
Total No. of Samples	84
Training data Size	70
Testing data Size	14

3.4.2 STEP 2: K-MEANS CLUSTERING ALGORITHM

The Knee Quality Metric alone is not sufficient to determine the severity of the Knee. Age and BMI of the user are two other crucial parameters that have to be considered to determine the accurate severity of the knee. Here, K-means clustering algorithm is further used on the obtained Knee Quality Metric (KQM), age, and the BMI from the training data to obtain different clusters. Each cluster is a function of age, BMI, and Knee Quality Metric. Fig. 7 shows the 3-D representation of the different clusters obtained. Each cluster in the figure is denoted by a different color. The Z-axis represents the KQM, The X, and the Y axes represent age and BMI respectively. The red, maroon and blue clusters are situated in the upper region of the plot signifying a higher value of KQM over a range of age and BMI. The lower part of the graph consists of orange, purple, and green clusters – signifying a lower

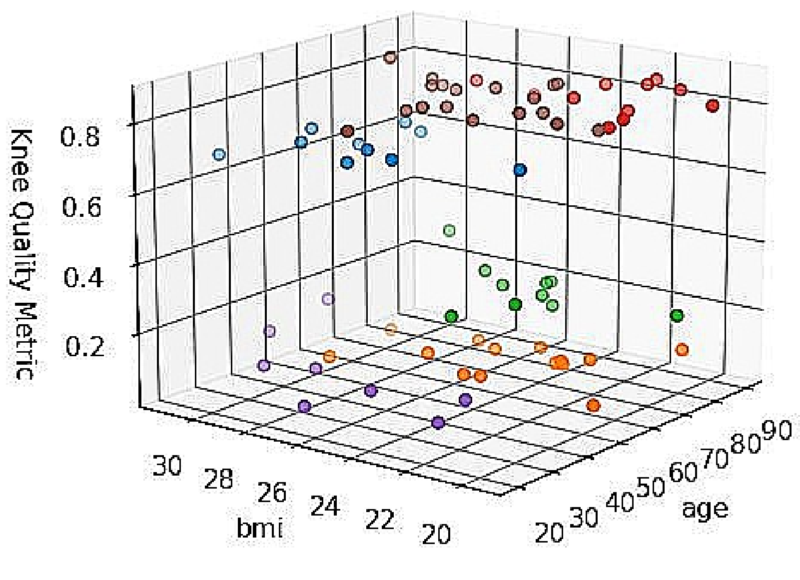


Fig 3.7 Plot of Clustered Data by K means

value of the KQM over a range of age and BMI values.

Table 3 shows the inference made from the clusters obtained. It is observed that age and the minimum KQM factor significantly in determining the severity of the affected knee. The threshold angle defines the maximum leg extension the user's leg can withstand. It is directly related to the KQM.

Table 3. Inference from the obtained clusters

Cluster	Lower Age limit	Upper Age Limit	Lower BMI limit	Upper BMI limit	Minimum KQM value	Threshold Angle
0	28	54	23.72	30.12	0.81	-26
1	66	83	21.22	25.29	0.06	No Therapy
2	47	88	24.8	27.6	0.18	-54
3	42	75	21.83	27.21	0.73	-30
4	25	46	23.11	28.04	0.05	No Therapy
5	70	85	22.27	29.10	0.88	-20

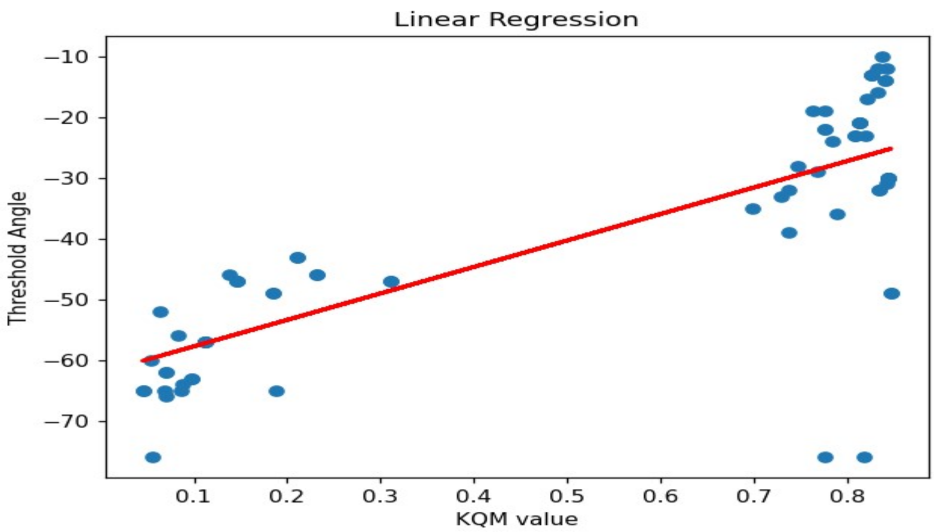


Fig 3.8 Linear Regression between angle and KQM

These threshold angles are determined by running a Linear regression taking angles as the function of KQM. (Fig. 8) shows the Linear regression graph

3.5 Physiotherapy Phase

During the calibration phase, the gyroscope data of the user is fed into the CNN and the KQM is obtained. Post this phase, the cluster is determined based on the obtained KQM, age, and the BMI of the user. The maximum leg extension threshold angle is determined based on the cluster. For each cluster, corresponding physiotherapeutic routines are pre-programmed into the ESP32 keeping the following attributes in mind:

i. Age of the User
ii. Leg extension threshold angle
iii. Sex of the User
iv. BMI of the User
v. whether the User underwent recent Knee surgery
vi. whether the User was recently injured?

Once the Leg extension threshold angle is determined based on the cluster, the particular physiotherapy routine corresponding to that cluster is set in the micro-controller. As shown in Fig. 9 when the user initiates the exercise routine through the GUI, automated physiotherapy is started. The cycle of continuous extension and retraction of the leg is done by the Linear Actuator. A fixed number of cycles are repeated which is already pre-set. The amount of extension is controlled based on a simple feedback mechanism. As soon as the sensor reads an angle equal to the threshold angle, the linear actuator retracts to its initial position, and the cycle

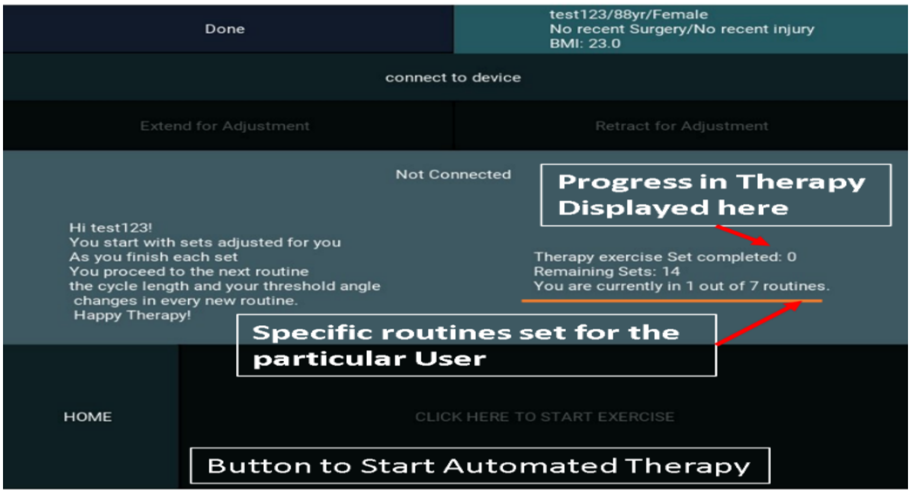


Fig 3.9 Physiotherapy Section in the GUI

repeats.

The leg extension threshold angle is gradually increased throughout the physiotherapy which would last from 7days to a month, depending on the severity of the knee determined by the obtained cluster.

CHAPTER 4: RESULTS AND DISCUSSION

RESULTS AND FUTURE WORK

The training data was split into 70 training samples and 14 testing samples. The training accuracy achieved was 97.33% and the accuracy on the test data was 90.21%. Further, our system experimented on 10 individuals of ages 20-60.

Healthy Subjects:

Table 4. Results obtained from users with a healthy knee

Name	Age	BMI	Predicted KQM	Threshold angle
User 1	34	24.4	0.187235937	-53.827927
User 2	53	21.4	0.1464535	-55.708813
User 3	21	26.7	0.045459315	-60.36667
User 4	67	22.56	0.21059303	-52.750694
User 5	71	25.6	0.070191309	-59.22603

From Table 3, The average range of motion of the knee approximates 50-60 degrees (negative sign is due to the direction of motion) from the initial position which can be understood by referring the Fig. 4 in the above sections. The severity of the knee can be determined by the KQM (>0.04 and <0.25) index mentioned above which proves the smooth flexion of a healthy knee.

Affected Knee:

Table 5. Results obtained from users with Affected Knee

Name	Age	BMI	Predicted KQM	Threshold angle
User 1	65	21.6	0.830914855	-24.14141707
User 2	53	30.1	0.844910085	-23.49595626
User 3	34	27.2	0.837528229	-23.8364079
User 4	21	23	0.7021234	-30.0812862
User 5	32	26.5	0.76	-27.41201416

The trend of data in the Table 5 speculates that an affected knee has a comparatively high KQM index (>0.70) as the average range of motion of the knee angle ranges from 20-30 degrees (negative sign is due to the direction of motion to plane). Figure 5a. substantiates the condition of the knee as the patient cannot flex it beyond 30 degrees due to the severity.

To analyze whether the severity is high or low we feed this raw data into our system which is dimensionally clustered by considering all the other characteristics fed by the user which helps in computing the KQM index. Other causes such as previous injuries, ailments, etc. are used to substantiate the data obtained after training.

Example in the case user 4 according to the table the age and BMI are normal but the threshold angle and KQM index indicates the severity as otherwise, to prove that data produced is accurate, the attributes and their values fed into the system supports to deduce the amount of severity. This example indicates that with reference to a healthy knee this is affected due to knee injuries posed in the past. Whereas in case of user 1 due to the age characteristic we can conclude that the most probable outcome of severity is based on age and BMI index.

The system dynamically interprets and deduces the appropriate physiotherapy routine required for an affected knee based on our KQM index. This algorithm concludes to its result keeping in correlation with the pre-programmed attributes.

The training data was split into 70 training samples and 14 testing samples. The training accuracy achieved was 97.4% and the accuracy on the test data was 94.5%.

CHAPTER 5:
CONCLUSION

Conclusion and Future Work

The conceived design for an automated knee physiotherapy machine was implemented successfully. The ergonomic design along with the accurate machine learning algorithm provides a much more elegant and robust solution compared to conventional means of physiotherapy. The cost for a session was significantly reduced and the portability of the apparatus makes it easily accessible to all demographics.

The prototype made works perfectly with adult legs. It provides slow and continuous passive motion which is as per the requirement of physiotherapy. The machine moves the foreleg to and fro in a slow and systematic manner so as to provide enough motion to the weak joint. This helps in improving the mobility of the joint and also the strengthens the muscles. The continuous passive motion provided also helps in healing of any damaged cartilage. Repeated use of the machine can prove to be effective in relieving knee pain. The Bluetooth application along with the ergonomic design of the model make this a simple to use and portable alternative to conventional physiotherapy techniques. The modularity of the model makes it more flexible, so that it can be used on any chair, regardless of the height.

The work we have done effectively acts as a way to help all people in need of knee physiotherapy. With our project, we have made it affordable and also readily available for anyone suffering from knee problems to get the best treatment they can.Further clinical trials are required to estimate the effectiveness of the device as compared to its traditional counterparts and much more data must be collected to further improve the accuracy of the Machine learning model.

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