Dataset Collection and Mechanism Design for Semi-Automation of Prosthetic Pneumatic Knee Joint

Author

MUHAMMAD HAMZA QURESHI

00000277647

Supervised by

Prof. Dr. Mohsin Islam Tiwana

MASTERS IN MECHATRONICS ENGINEERING,

DEPERTMENT OF MECHATRONICS ENGINEERING,

COLLEGE OF ELECTRICAL & MECHANICALENGINEERING,

NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY,
ISLAMABAD, PAKISTAN.

AUGUST 2022

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by Mr. Muhammad Hamza Qureshi, (Registration No. 0000277647), of College of Electrical and Mechanical Engineering CEME has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is within the similarity indices limit and is accepted as partial fulfillment for the award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature: ______________________________

Name of Supervisor ________________________

Date: ________________________

Signature (HoD): ________________________

Date: ____________________________________

Signature (Dean/Principal): __________________

Date: ____________________________________

Acknowledgements

First and foremost, glory and gratitude to God, Allah Almighty, for showering His blessings on me during my research work, allowing me to successfully complete the research.

I would like to express my heartfelt gratitude to Dr. Mohsin Islam Tiwana, Ph.D., Associate. Professor and HOD Research at NUST College of EME, for allowing me to conduct research and providing invaluable support in the process. His dynamism, vision, honesty, and inspiration have all left an indelible impression on me. Working and studying under his supervision was a great honour and privilege. I am thankful for everything he has done for me.

I owe my parents a debt of gratitude for their devotion, prayers, care, and sacrifices in educating and training me for the future. My mother and father deserve special thanks for their prayers, understanding, and ongoing concern, inspiration, and assistance in helping me finish this research project. I would want to thank my brothers and sister for their love and prayers. My heartfelt gratitude goes out to my friends and colleagues for their unwavering commitment to seeing this thesis through to completion.

I owe special thanks to my employer National Radio and Telecom Corporation, my HOD for allowing me and supporting me during my master's degree, and all my colleagues for their assistance during research work in all aspects.

I also owe special thanks to all the participants who assisted me in collecting the dataset for this research.

This work is devoted to my adored parents and cherished siblings,

who have always encouraged me to do amazing things.

Abstract

This work presents the process of dataset collection for the Human Activity Recognition (HAR) including walking, running, stair climbing up and stair climbing down. The data is collected via IMU sensors mounted on lower limbs and upper limbs. The dataset is collected to train an algorithm for implementation on prosthetic knee joint to assist amputees in auto calculation of gait pattern. A passive pneumatic knee joint is used to semi automate it. This is done by designing a mechanism for controlling the damping of pneumatic knee joint. The two damping screws i.e., flexion, extension, are located on the rear of knee joint. In the scope of this project, they are controlled via selection switch assembly.

Key Words: *Human Activity Recognition (HAR), Inertial Measurement Unit (IMU), Pneumatic Knee, Semi-Automation, Semi-Active Prosthesis, Mechanism*

Table of Contents

Contents

List of Figures

List of Tables

Acronyms

ADL	Activity of Daily Living
BDPL	Back Drivable Prosthetic Leg
BDM	Bayesian Decision Making
CNN	Convolutional Neural Network
CSV	Comma Separated Values
DTW	Dynamic Time Warping
HAR	Human Activity Recognition
HD	Hip Disarticulation Prosthesis
HP	Hemipelvectomy Prosthesis
IMU	Inertial Measurement Unit
K-NN	k-Nearest Neighbor Algorithm
LPK	Leeds Prosthetic Knee
LSM	Least Square Method
PCA	Principal Component Analysis
SVM	State Vector Machine

Chapter 1: Introduction

The abbreviation HAR represents Human Activity Recognition, which is a vast field being used now a days for multiple purposes such as health care, sports [1] etc. In health care the use of HAR is in the activity / fall detection of elderly patients [2], [3] which helps researchers in finding useful data for treatment [4]. Another use of HAR in health care is in rehabilitation in aiding or assisting amputees to live like a normal life [5].

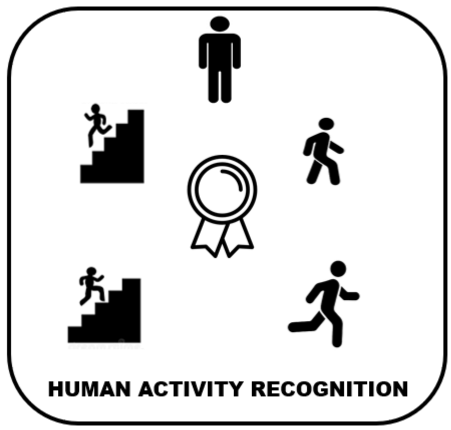


Figure 1-1 HAR

In the research carried out here shall be focusing on the use of HAR in rehabilitation. As per the survey of [6] there has been 57.7 million amputees around the globe. In health care sector, Human Activity Recognition, is of great importance for the amputees with artificial limbs. After having prosthetics, the next challenge for the amputees is to perform their daily life activities like normal human beings. So, for amputees to perform their daily life activities, the activity pattern of normal human beings is required to be recorded and the replicated on these amputees, which is only possible through HAR. This helps amputees to boost up their confidence and also help them to work actively in public [7]. During the rehabilitation of an amputee the physician accesses the level of amputation in amputee. There are five levels of amputation named as K0, K1, K2, K3, and K4. Where, K0 is the level in which amputee does not need assistance in ADL while in K4 the amputee is fully dependent on support [8].

1.1 Problem Statement

The mobility of human being is solely dependent on the lower limb activity of an individual. All the daily routine tasks are executed smoothly via the movement which is severely difficult for the individuals with lower limb amputation. Apart from the psychological trauma, lack of ability to do your daily life activities, significantly affects the requisite functionality of an individual as a member of society. Moreover, this limitation in mobility restricts an amputee individual in his capability of doing daily life activity and limits his/her chances of employment leading him/her not to live a healthy life. Thus, an amputee wears prosthetics to overcome/ enhance his chances of activity of daily living (ADL). So, the prosthetics play an important role in helping amputees to a life very close to a normal human life and known as artificial limbs. By wearing these prosthesis, the patient (amputee), is able to keep his/her posture erect and maintain balance [9].

There are three [8] types (some other types of lower limb prosthetic systems are discussed in section 3.1) of major prosthetic systems based on the design of system:

1. Passive Prosthesis
2. Semi-Active Prosthesis
3. Active Prosthesis

Semi-Active prosthesis, include the involvement of actuators (i.e. motors) along with other passive components, while passive systems include pneumatic, hydraulic system or other passive components to provide the assistance in mobility [10]. In this study we shall be discussing and working on a pneumatic knee joint.

The pneumatic knee joint, as shown in Figure 1-2, is adjusted individually for each amputee for his different phases of movement i.e., walking, running, stair-climb-up, stair-climb-down, eating etc. this is a time taking process which consumes a lot of time of the amputee in adjusting appropriate pressure for easy and comfortable movement.

Two damping adjustment screws i.e., flexion and extension are provided on the back side of the system as shown in Figure 1-2. These screws are adjusted for both flexion and extension phases of various movements. So, the problem statement for this research study is:

To collect a dataset for HAR, design and control a mechanism for pneumatic knee joint, help the amputees assist in auto-adjustment of damping for movement of various ADL i.e. walking, jogging, stair-up, stair-down

1.2 Objectives

This research constitutes of the following objectives:

- ❖ Study of dataset collection procedures for HAR
- ❖ Design of appropriate hardware for collection of dataset
- ❖ Collection of datasets for HAR
- ❖ Study of mechanisms for semi-active prosthetic knee joints
- ❖ Design of mechanism for semi-automation of pneumatic knee joint

❖ Testing of designed hardware mechanism on pneumatic knee joint

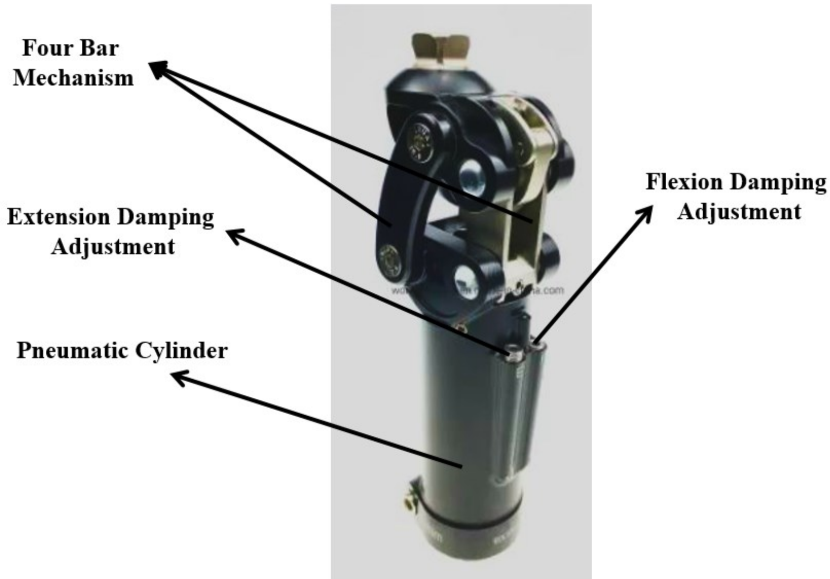


Figure 1-2 Labelled Pneumatic Knee Joint

1.3 Literature Survey

This thesis comprises of two phases. In the first phase, dataset regarding the human activity recognition has been recorded while in the second phase the working on designing and fabrication on the semi-automation of pneumatic knee joint has been done. So, the literature review shall also be divided into two phases as described above respectively.

Researchers have put forward various types of designs for HAR [11] dataset recording above and below knee amputees. Different types of HAR based hardware designed and used in literature are discussed below, while above/below knee prostheses are discussed in section 3.1.

In [12], the authors have used 5 Xsens [11] sensors for collection of dataset, the dataset is collected indoor and outdoor with recording of six activities i.e. jogging, skip, walk, stair-up, stair-down. Only 4 test subjects were involved in collection of datasets for this study.

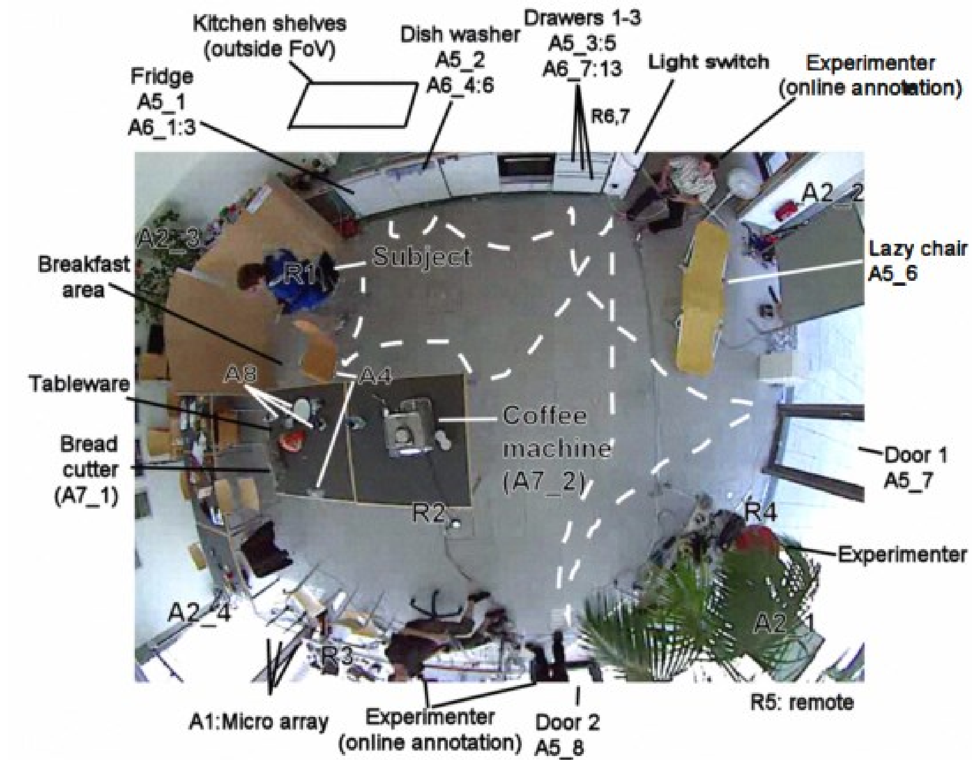


Figure 1-4 Environment Setup for Data Recording [12]-[14]

During this study an open-source dataset [13], [14] has been used with the name of opportunity dataset. A shirt, as shown in Figure 1-3, with embedded sensors has been designed in this study, this helps in the easy placement and removal of sensors from the participant. A total of 5 sensors have been mounted on the shirt, while 24 [14] have been used to recording of data. The environment where the data has been recorded is shown in Figure 1-4.

Another research [15] has shown that there are various errors that could occur while recording a dataset. There errors are:

a. **Overfill:** It occurs when the start or stop time of the label is earlier or later than the actual time.

b. **Under-fill:** It occurs when the start or stop time of the label is earlier or later than the actual time.

c. **Insertion:** Predicting an action when there is no activity of interest (i.e., null class).

d. **Merge:** When subsequent actions of class are recognized as single one (i.e., ignoring the null class between them).

e. **Fragmentation:** Predicting the null class in between an uninterrupted activity class.

f. **Deletion:** Assigning a null label when there is an activity.

g. **Substitution:** When an activity is misclassified as a different class (other than null).

In [16], the authors have used 5 Xsens [11], which includes tri-axial accelerometer, tri-axial gyroscope and tri-axial magnetometer, sensors for collection of dataset, which was recorded in Bilkent University Sports Hall, in the Electrical and Electronics Engineering Building, and in outdoor with flat ground. The placement of sensors can be seen in Figure 1-5. A total of nineteen activities have been recorded in this study i.e., sitting, standing, lying down on back, lying down on right side, ascending stairs, descending stairs, standing in elevator still, moving around in elevator, walking in a parking lot, walking on treadmill (flat), walking on treadmill (inclination 15º), running on treadmill @4kmph, running on treadmill @8kmph, exercise on stepper, exercise on cross trainer, cycling on exercise bike horizontal, cycling on exercise bike vertical, jumping and playing basketball. Eight

Figure 1-5 Sensors Placement [16]

participants have taken part in recording these activities. Different algorithms have been applied for analysis of data including BDM, K-NN, and SVM which gave results from 98.5% to 99%.

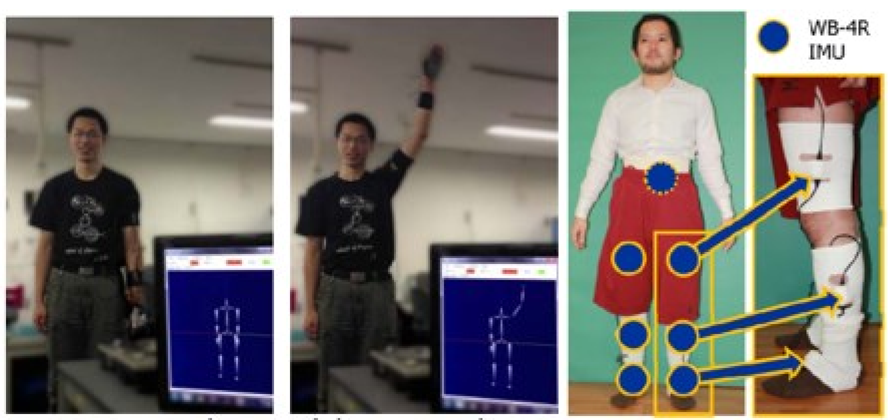


Figure 1-6 (a) IMU based Motion Capture System (b) Placement of 7x Sensors [17]

In [17], the authors have used 7 WB-4R IMU sensors. Two experiments have been performed, in first experiment the comparison of marker based HAR and marker-less HAR is compared while in second experiment the dataset is collected with IMU sensors. The data has been collected in indoor and outdoor environment and their pitch angles have been compared. The placement of sensors is shown in Figure 1-6.

In [18], the authors have used only 1 IMU (MPU 6050), with customized sensor and control board for dataset collection and data is recorded for six ADLs i.e., walking, walking upstairs, walking downstairs, sitting, standing, and lying. The sensor board is

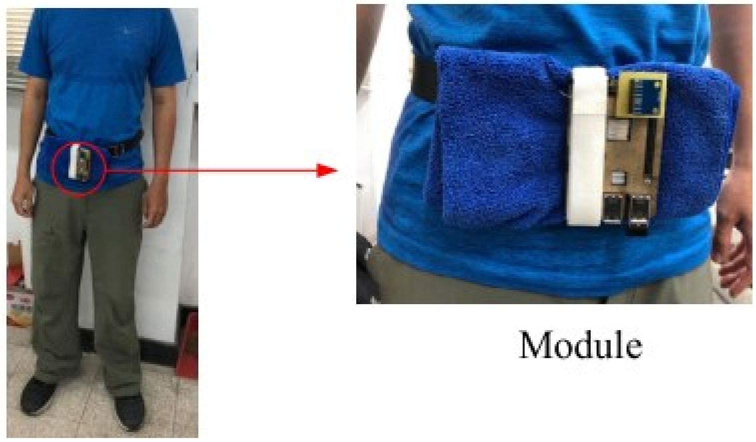


Figure 1-7 Placement of 1x Sensor on Waist Line [18]

mounted on the waistline, shown in Figure 1-7, of all the 21 participants who have taken part in recording this dataset, and it was assured that the position and direction of sensor mounting must be fixed for each participant so that there may be minimal garbage values during data recording. The results of accuracy obtained from this study varied from 93.99% to 95.99%.

In [19], the authors have used 8 sensors, shown in Figure 1-8, for dataset recording, IMUs has been used as sensor while 5 individuals have taken part for recording of dataset. Nine ADLs have been recorded here which includes walking upstairs, walking downstairs,

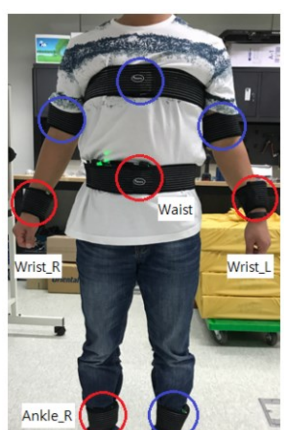


Figure 1-8 Placement of 8x IMU sensors [19]

walking, sitting, eating, driving (driver), moving (passenger), standing, and lying. The results of accelerometer, magnetometer and gyroscope were calculated separately which were 92.18%, 85.22% and 78.33% respectively. This shows that the results for HAR are more accurate with accelerometer.

In [20], the authors have made a comparison among the vision based and sensor based [21], [22] HAR. They have divided vision-based systems into two types i.e., marker-less system and marked-based system. These vision-based system are usually expensive in terms of cost and processing data. For using sensor-based systems the researchers have used different number of IMU [23] sensors and the results of these sensor-based systems depend upon the accuracy of IMUs. For comparison the authors have used IMUs (shown in Figure 1-9 (a)) and goniometer as sensor based, Reha@home (shown in Figure 1-9 (b)) and Kinovea (shown in Figure 1-9 (c)) (Markers) as vision-based analysis. In the sensor-based system it was concluded that the results of IMU is more accurate while vision-based systems require less complex environment for more accurate results.

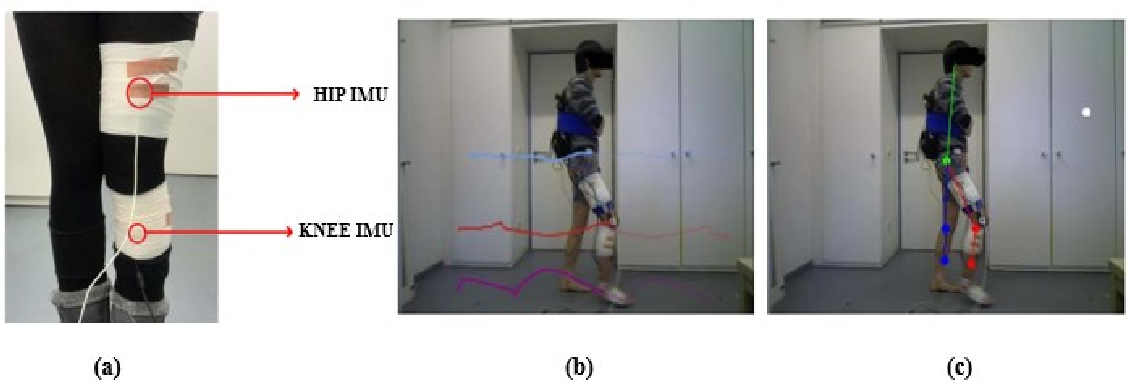


Figure 1-9 (a) Placement of 2x IMU sensors (b) Data Recording via Reha@home (c) Data Recording via Kinovea [20]

In the second part of the literature review there shall be discussed different types of lower limb prosthesis and the work done by researchers in the past on designing and development of various lower limbs.

There are five [24] types of lower limb amputations, based on which lower limb prosthesis are defined:

a. Hemipelvectomy amputation

b. Hip disarticulation amputation

c. Above knee amputation

d. Below knee amputation

e. Symes amputation

1.3.1 Hemipelvectomy amputation

In this type of amputation, the removal of half of pelvis and entire lower extremity is involved. Gluteus maximus is usually necessary to remove in this case due to trauma or some disease. In this case the stump consists of the skin covered abdominal cavity. While designing the prosthesis for this type of amputee, the designers try to design the socket which put weight bearing load directly on the bony structure, extending the socket to the rib cage (which helps in absorbing the load). The method discussed later cause the limitation in the body motion and restricts heat dissipation [25]. So, the prosthesis used for this type of amputation is Hemipelvectomy prosthesis. Figure 1-10.

1.3.2 Hip disarticulation amputation

In this type of amputation, the removal of lower limb through the hip joint is involved. Hip disarticulation has been the classic procedure for treatment of distal femoral osteosarcomas i.e., for treatment of tumor of distal and proximal femur [26]. So, the prosthesis used for this type of amputation is hip disarticulation prosthesis. Figure 1-10.

1.3.3 Above knee amputation

In this type of amputation, Above-knee amputation, also known as transfemoral amputation, is most often performed for advanced soft-tissue sarcomas of the distal thigh and leg, or for primary bone sarcomas of the distal femur and proximal tibia. Above-knee amputations may be performed through the distal aspect of the femur (supracondylar), the middle section of the femur (diaphyseal), or just below the lesser trochanter (high above-knee) [26]. So, the prosthesis used for this type of amputation is above knee prosthesis or transfemoral prosthesis [8]. Figure 1-10.

1.3.4 Below knee amputation

Below-knee amputation, also known as transtibial amputation, is usually performed for extensive high-grade soft-tissue sarcomas of the lower leg, ankle, or foot. Primary bone sarcomas rarely occur in these locations. Extensive infiltration of tendons and ligaments and around bones in this area may preclude a functional extremity following wide excision [26]. Below knee prosthesis also known as transtibial prosthesis [24]. Figure 1-10.

1.3.5 Symes amputation

Symes amputation (SA), also known as ankle disarticulation, which is done at the level of

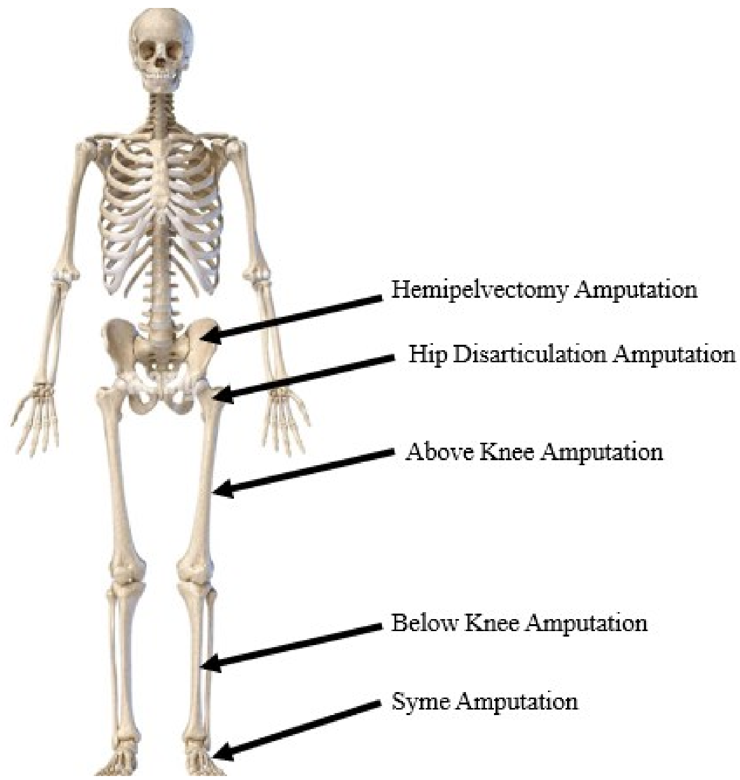


Figure 1-11 Lower Limb Amputation

the ankle joint in which there is removal of malleoli, and the heel pad is protected. It is performed based on indications particularly in pediatric population. SA has the advantage

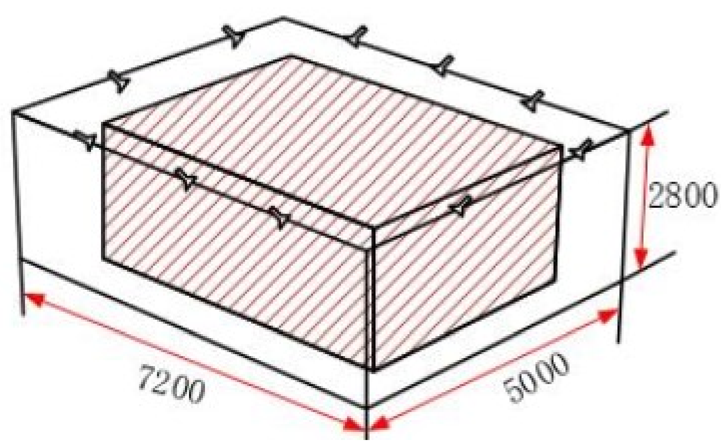


Figure 1-10 Layout Space for Experimental Setup (Dimensions in mm) [27]

of permitting weight bearing without prosthesis [24]. So, the prosthesis used for SA is known as the Symes Prosthesis. Figure 1-10.

In [27] the researchers have used optical 3D method for collection of data of HAR for human lower limbs. For this purpose, researchers have used vision-based sensor i.e., Nokov technology, which has been designed by Chinese. It is a 3D motion capture system, which uses several cameras to record marked points. These recorded points are then

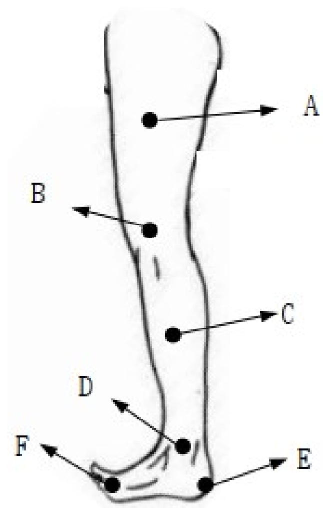


Figure 1-13 Markers for Data recording (A-- Thigh, B-- Knee, C-- Calf, D-- Ankle, E-- Heel. F-- Front Foot) [27]

Figure 1-12 Transfemoral Prosthesis [29]

processed on a computer for extraction of several features such as velocity, position, and acceleration etc. An environment with size of 7200 mm x 500 mm x 2800 mm has been defined for data recording covered by a total of ten cameras. The sketch of this is shown in figure. A total of six markers have been placed on the body for tracking, as shown in Figure. The data has been recorded for six activities i.e., walking, upslope, and downslope, upstairs and downstairs. For designing the mechanism of knee joint prosthesis 4-bar, 5-bar or 6-bar [27], [28] mechanisms are usually used. In the current study the researchers have designed a mechanism using 6-bar mechanism. MPU6050 is used as an IMU sensor, STM32 as controller, and Bluetooth has been used as communication module for communication between the prosthetic knee and personal computers.

In [29] the researchers have designed an above-knee prosthetic joint as shown in Figure 1-13. The upper and lower part of the joint are connected via a pin joint. There is a lead screw which is used to hold the position of knee joint during and after motion. The lead screw is acting as output shaft of an actuator which controls the position of joint. The material used to design this prosthetic is Aluminum 6061 due to its light weight and easy manufacturing.

In [8] the researchers have used Leeds Prosthetic Knee (LPK), which is a semi-active prosthesis, for analysis of energy consumption of knee joint. The system comprises of

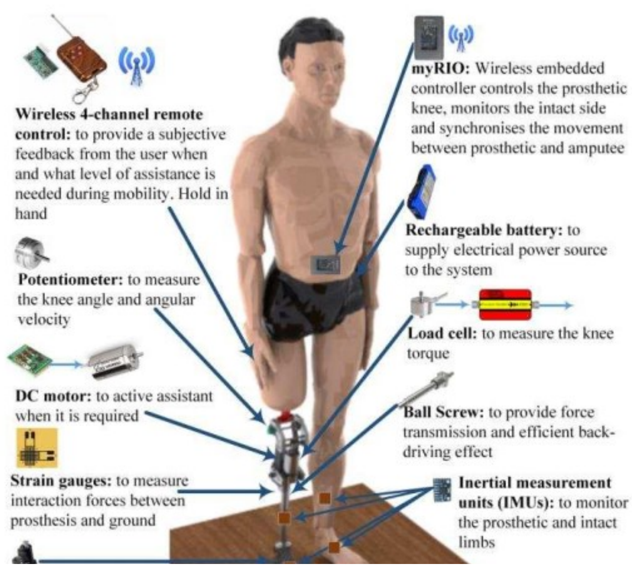
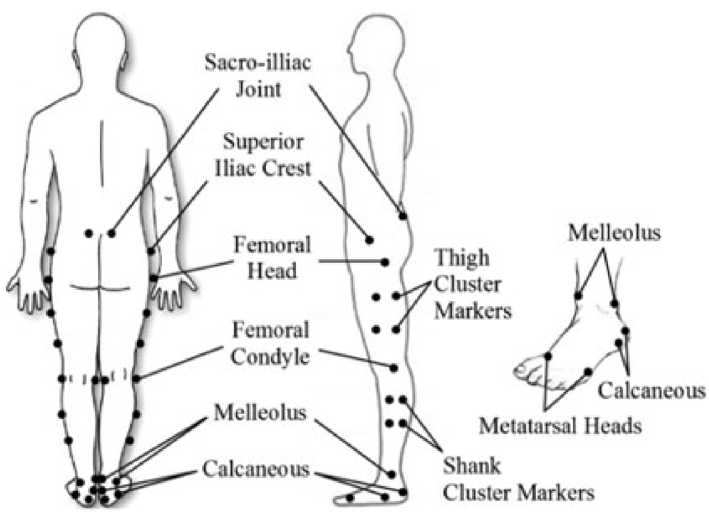


Figure 1-14 Labelled Diagram of designed system [8]

IMU sensor, DC gear motor, Potentiometer, Strain Gauge, myRIO and Wireless 4-channel remote control. Based on the testing of the knee it was found that semi-active system is back drivable i.e., it stores energy in negative energy cycle while it provides energy in positive cycle.

In [30] the authors have designed a semi-active prosthetic knee joint with dual (active and passive) mode of working. The authors have collected the dataset for optimization of the system in level ground walking. A total of four participants took part in the data collection using visual based motion capture system. The placement of markers for visual sensors is shown in figure. The above knee prosthesis has been designed, shown in Figure, to study the effects of dynamic coupling between the amputee body, the ground, and the prosthesis.



(a)

(b)

Figure 1-15 (a) Placement of Markers for Data Recording (b) 3D CAD Model of Prosthetic Knee [30]

1.4 Thesis Layout

Throughout the early chapters of this thesis, several topics, and their relevance to the process of dataset collection for HAR and 3D CAD design for prosthetic knee joint for amputees will be introduced. This includes information on the dataset collection mechanism, setup, and knee joint design with necessary background theory. The following chapters then discuss the methods employed and the results obtained using these methods.

Chapter 1: Starts with a brief introduction about the research topic and sets the sight for the study by reviewing the literature concerning previous studies of HAR and mechanical mechanism for lower limb prosthetics.

Chapter 2: Introduces the mechanisms and methodology for collection of datasets in the literature and the methodology used in current study.

Chapter 3: Introduces different CAD designs of prosthetic knee joints and the methodology used for designing the mechanism of controlling the pneumatic pressure along with the mechanical design.

Chapter 4: The experimental setup for testing the mechanism for three different HAR positions shall be discussed.

Chapter 5: The results obtained, conclusion drawn during and from this research work and future recommendations shall be discussed here.

Chapter 6: Bibliography/ References of whole research work is given in this section

Chapter 2: Human Lower Limb Anatomy & Hardware Design for Dataset Collection

2.1 Human Activity Recognition (HAR)

Now a days much research has been carried out for HAR. Researchers have been working for getting data and analyzing this to recognize different activities of daily living (ADL), to assist, caring of elders in home-oriented health monitoring services or detect some serious illness in advance [21], [22], [31]–[33], the amputees to live a normal healthy life and to track the motions and movements of athletes [31].

In elderly care, the HAR is widely used for helping health care professionals to get the data of elder people and help them analyze their activity whether close to normal humans or deviating from it and in long term this helps professionals in getting the advance indication of any sort of abnormality. In case of elderly people in many cases it is difficult to get cooperation for recording data via sensors based methods, due to which many researchers have worked on vision based systems for this purpose as discussed in [32]. There are also some pros and cons of using sensor-based systems in elderly care system i.e., upper body movement may be neglected while wearing sensor on waist while wearing sensors on wrist may also make lower body activity undetected. Due to these reasons many researchers have suggested the use of hybrid systems such as use of cell phone and vision-based systems to cater for these issues. The elderly people can live independently in smart homes having variety of sensors in them. This can be achieved with very smart and advanced algorithms which can detect more accurate activities inside home.

It has been claimed in [33], that the device designed by the authors can be used to monitor solitary life of elderly people. The authors have used three accelerometers and an RFID reader to monitor ADL of elderly people. Overall, six activities from 15 subjects have been recorded and the overall results have the overall accuracy of 93.8%. The accelerometers used by authors is shown in Figure 2-1.

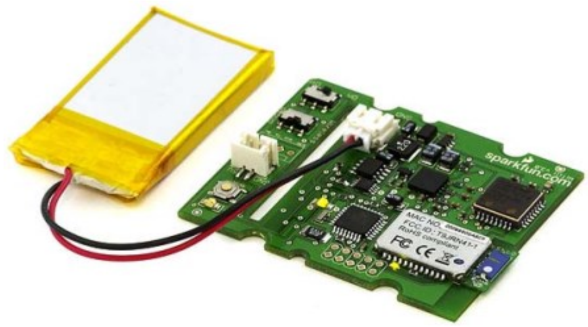


Figure 2-1 Bluetooth Based Tri-axial accelerometer [33]

2.2 Commonly used Anatomical Terminology

Any discussion of anatomical structure requires the use of certain standard descriptive terminology. Before proceeding, it is necessary to introduce some of this terminology as shown in Fig. 2-2. Slight variations in terminology exist between published descriptions, but the following definitions will be used throughout this work [34], [35].

2.2.1 Sagittal Plane

Any vertical plane passing through the body in an anterior-posterior direction and thus separating right and left portions of the body [35].

2.2.2 Coronal Plane

Any vertical plane passing through the body in a superior-inferior direction and thus separating anterior and posterior portions of the body [35].

2.2.3 Transverse Plane

Any horizontal plane passing through the body at right angles to the previous two and thus separating superior and inferior portions of the body along with the anatomical planes, three anatomical axes are also defined [35].

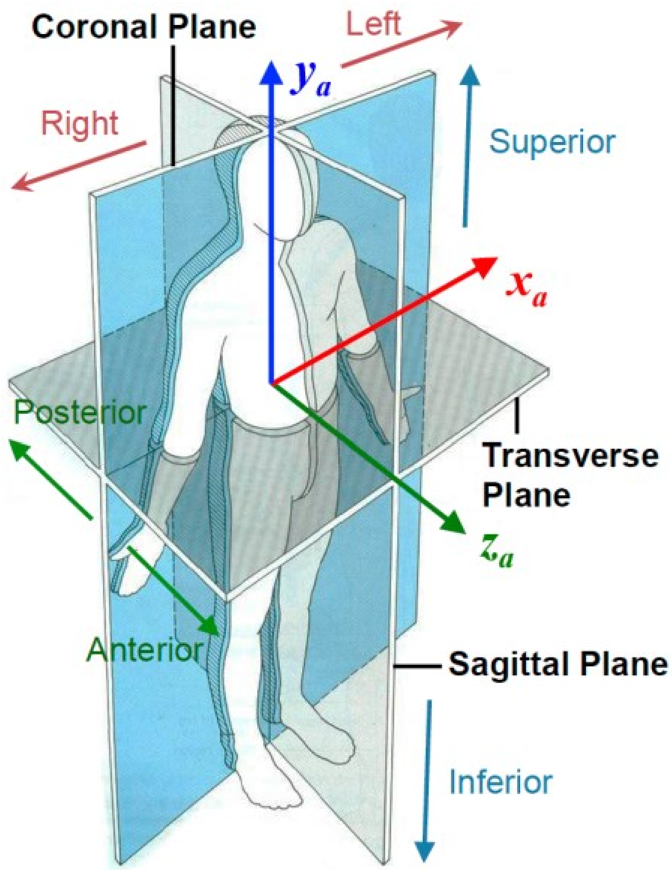


Figure 2-2 Human Anatomy Planes [34]

It is also necessary to clarify the terminology used when describing human movement at this stage. Complex geometric rotations like those which occur at the joints of the human body are not additive but are sequence dependent and this can result in highly complicated methods for the description of the motion. Traditionally however, the standard approach is to describe any motion as a projection in one of the anatomical planes previously discussed.

To clarify this description, it is necessary to define the 'anatomical position'. In this position the body is viewed from the anterior surface with the hands at the sides, palms facing forward. This is often used as position when studying or describing motion of the upper limb. Fig. 2.2 aids in the understanding of the following descriptions of lower limb motion, showing rotations in relation to the anatomical position.

2.2.4 Flexion \ Extension

These describe the motion of the lower limb forwards (flexion) or backwards (extension) in case of hip joint while in case of knee joint proximal (flexion) or distal (extension), Figure 2-3, in the sagittal plane, as shown in the anterior view in Figure 2.2 [36].

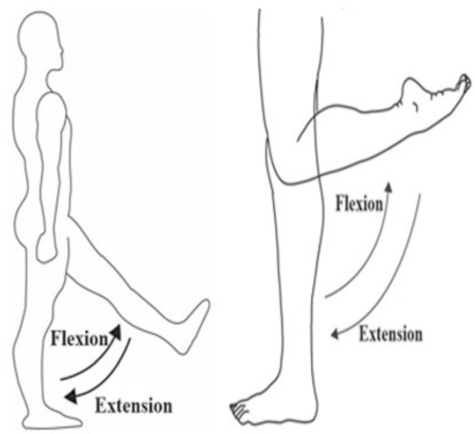


Figure 2-3 Lower Limb Flexion and Extension [36]

2.2.5 Abduction \ Adduction

These describe the motion of the lower limb medially (adduction) or laterally (abduction) Figure 2-4, in the coronal plane. Most studies assume a very little [37] abduction or adduction at the knee, there is an apparent abduction when the knee is fully extended, known as the carrying angle [36].

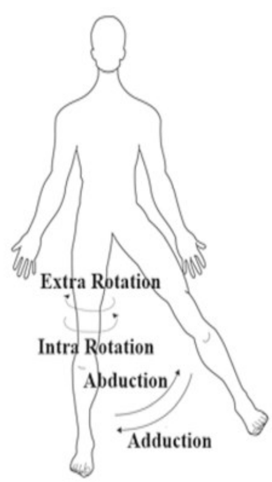


Figure 2-4 Lower Limb Abduction/Adduction and Intra/Extra Rotation [36]

2.2.6 Internal \ External Rotation

This is the motion that turns the lower limb at hip joint. The rotation of lower limb away from hip joint is known as internal rotation while the rotation of lower limb towards hip joint is known as external rotation [38], these two motion occur about sagittal plane Figure 2-4 [36].

Figure 2-5 Human Leg Anatomy [38]

2.2.7 Lower Limb Bones

Human lower limb consists of overall 30 bones [35] out of which we shall discuss just three major bones namely as Femur, Tibia and Fibula, as shown in Figure 2-5. The Femur bone is the bone which connects hip joint with the knee joint, it is the part of upper leg often also known as thigh. The bone tibia, the inner bone, is the larger and stronger bone of lower limb. It is also known as shin, and it bears most of the body weight in lower leg [39], [40]. The bone fibula, the outer bone, is the small bone of lower leg. Both tibia and fibula are connected to each other via ligaments [36],[41].

2.3 Range of Motion of the Human Lower Limb Joints

As for lower limb of human body there are three joints that exhibit motion while movement which include hip joint, knee joint and ankle joint. The motions of these joint occur about sagittal plane, transverse plane, and coronal plane. The range of moving degrees [42] of these three joints is shown in Table 2-1 and Figure 2-6.

Table 2-1 Range of Motion Human Lower Limb

Sr. No.	Joint Name	Range of Movement (Degrees)
1	Hip Joint	9° to -120°
2	Knee Joint	2° to 144°
3	Ankle Joint	40° to -15°

The maximum angle of movement for hip joint is required while performing squat lifting and sit-stand transition, including maximum flexion and extension at sit-stand and running

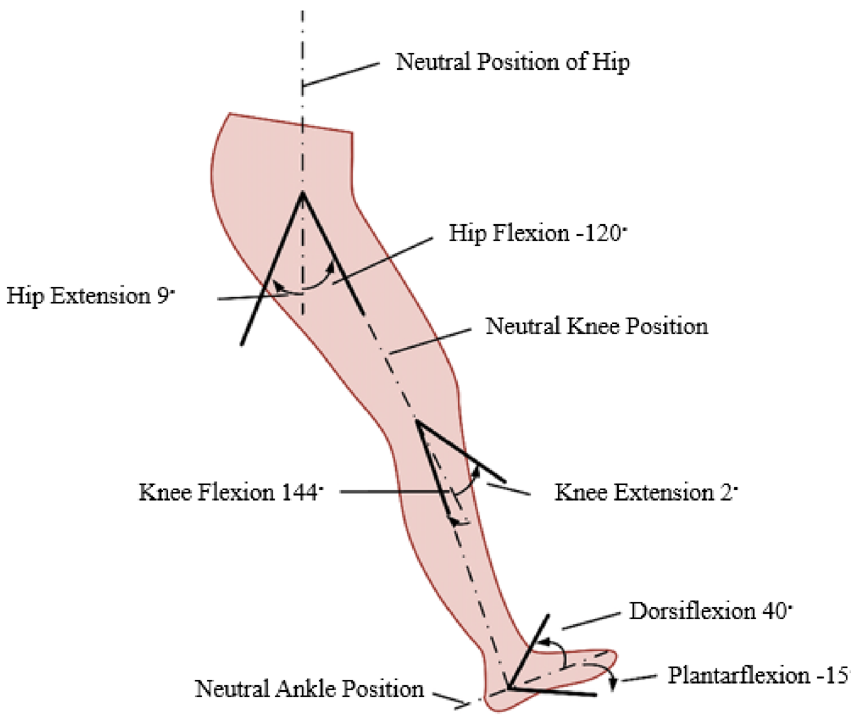


Figure 2-6 Range of Motion Visuals

respectively. On the other hand the maximum angle of movement for knee joint is required for squat-lifting, running and sit-stand transition, including maximum flexion occurring while performing squat lifting and max. extension is required for almost all movements [42].

Based on the data above it can be clearly seen that total movement angle of hip joint is approximately 129°, knee joint is 146° and ankle joint is 55°.

2.4 Customized Dataset Recording Hardware

After having complete and thorough literature review about the dataset recording, I then started working on designing customized hardware for recording the dataset, due to high cost of commercially available systems. From the literature review it was found that the use of vision-based sensors is very expensive [43] in terms of cost and computation also, it was decided to move forward towards the IMU based sensor system. Based on literature review [20], [23] it was found that the use of some wireless device would be suitable to read and transmit data for the server. Different types of hardware were designed for collection of data, and they are described as under:

2.4.1 Hardware Design-1

The idea of this design was to combine all the electronics in one enclosure including

Figure 2-7 Hardware Design - 1 PCB

batteries and battery charging modules as shown in Figure 2-7. The Table 2-2 shows the components included in this initial design.

Table 2-2 Components of Design-1

Sr. No.	**Hardware**	**Qty.**
1	ESP-32 Microcontroller	1
2	Li-ion Cells 18650	2
3	Li-ion Cell Charger	2
4	PCB Enclosure	1
5	MPU6050 gyroscope/accelerometer	1
6	Adjustable power supply module	1

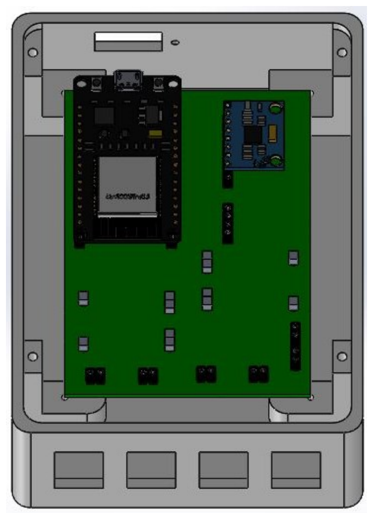


Figure 2-8 Hardware Design-1 PCB Enclosure

The designed hardware is shown in Figure 2-7 and Figure 2-8. Following issues have been found in this design for completion of dataset:

- The size of enclosure was too large as compared to the requirements of the current study.

Figure 2-9 Hardware Design - 2 PCB Design

- Due to large size of hardware the weight was also increased causing issues in data recording, especially while running. The hardware moves downward and was unable to retain its position.

Due to these issues this first hardware design was rejected, and another hardware was designed which is explained in heading.

2.4.2 Hardware Design-2

After the failure of initial design this new design with different strategy was designed. All the extra and unnecessary hardware such as battery charging module etc. were removed and just few components were included, which are shown in Table 2-3.

Table 2-3 Components of Design-2

Sr. No.	Hardware	Qty.
1	Esp32 Microcontroller	1
2	MPU6050 gyroscope/accelerometer	1
3	Electronics Enclosure	1
4	Power Bank (for powering up electronics)	1

A new PCB for mounting of ESP32 and MPU6050 was designed, and a new metallic

Figure 2-10 Hardware Design - 2 PCB
Enclosure

(Aluminum) case was designed which included the electronics as shown in Figure 2-9 and Figure 2-10.

Following issues were observed during data collection of the HAR:

- Due to metallic nature of PCB enclosure and despite of being small in size, the weight of the enclosure was still large which also could not maintain its position and moved from its position causing false data recording.

2.4.3 Hardware Design-3

After unsuccessful trails of hardware design-2 a new methodology for hardware design-3 was developed based on literature review of [18] and [19]. The hardware used in this third design is listed in table 2-4.

Table 2-4 Components of Design-3

Sr. No.	Hardware	Qty.
1	Esp32 Microcontroller	1
2	MPU6050 gyroscope/accelerometer	1
3	Li-ion Battery	1
4	ON-OFF Switch	2

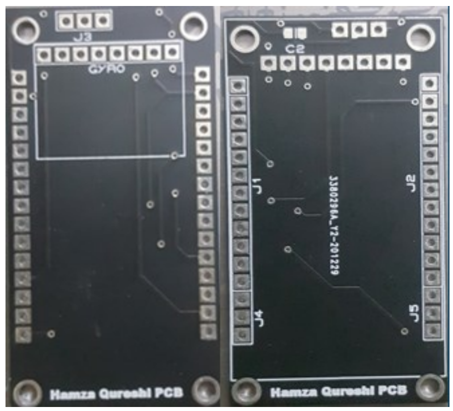


Figure 2-11 Hardware Design-3 PCB

This third design proved to be the final design and was finally used in the final dataset

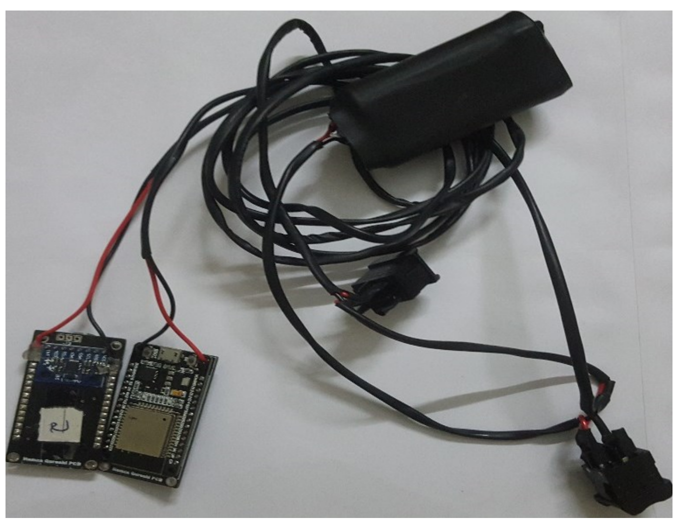


Figure 2-12 Hardware Design - 3

recording. The Figure 2-11 and Figure 2-12 shows the images of the designed hardware. The PCBs were mounted directly on the body of the participant via stretchable strap and data was then recorded. The battery was placed in the pocket of the participant while recording of data.

2.5 Data Recording

The recording of dataset was done according to the standard of WISDM dataset [44]. The format of this dataset is defined in the Table 2-5.

Table 2-5 Parameters of WISDM Dataset

Sr. No.	Field Name	Field Description
1	Subject id	Type: Numeric Value Description: this is the id/serial of the participant recording his data
2	Activity Code	Type: Activity Name Description: this is the name of the activity being recorded i.e., walking, running etc.
3	Ax	x-axis value of accelerometer
4	Ay	y-axis value of accelerometer
5	Az	z-axis value of accelerometer
6	Gx	x-axis value of gyroscope
7	Gy	y- axis value of gyroscope
8	Gz	z- axis value of gyroscope

So, in our study accelerometers were mounted on the sagittal plane and transverse plane of participant. There were two sensors used in each phase of data recording. The dataset recorded from each participant, was recorded in 3 configurations i.e.

Figure 2-13 Configurations: (Left) a) Configuration-I b) Configuration-II c) Configuration-III

2.5.1 Configuration I

One sensor mounted on femur of right leg [17], [20], [23], [45] and second mounted on tibia/fibula of right leg Figure 2-13.

2.5.2 Configuration II

One sensor mounted on humerus of right arm [19] and second mounted on radius/ulna of right arm Figure 2-13.

2.5.3 Configuration III

One sensor mounted on radius/ulna of each right and left [16], [19] arm Figure 2-13.

All the three configurations described above are implemented on the participants as shown in Figures 2-13. As said in [46] that any best activity can only be recorded on the place where it occurs. Taking into consideration that I have chosen to place sensors [43] on lower limb and upper limb because in my case the activities that are recorded, as written in table , occurs on the lower and lower limbs.

The dataset collected and its process shall be discussed in Chap 4.

Chapter 3: Design of Damping Control Mechanism

This chapter contains complete Design and Model of Damping Control Mechanism. It presents the literature review of similar designs, the components used in this mechanism.

3.1 Prosthetic Knee Joints

A best suitable knee must follow the behavior of a biological knee joint. Currently, a variety of prosthetic knees are available in market [29]. Following are the different types of prosthetic knees:

a. Single axis knee
b. Locking knee
c. Stance control knee
d. Polycentric knee
e. Pneumatic/Hydraulic knee
f. Microprocessor knee

A brief description of these knee joints is as follows:

3.1.1 Single Axis Knee

Single axis knee joints are the joints that bend freely. For movement stability using this type of knee the amputee must rely on muscles. This type of knee consists of a single pivot present between

Figure 3-1 Single Axis Knee [46]

the thigh and shank. This type of knee is usually used by the children having lower center of gravity [29], [47]. Figure 3-1, 3-6.

3.1.2 Locking Knee

This type of knee comes with a wire/cable or lever to keep them straight (locked) while moving and the wire/cable or lever is (unlocked) released to allow the amputee to have sitting posture. These are the most stable knees available. The amputees who have short residual limbs or poor hip strength use this type of knee joint [29], [47]. Figure 3-2, 3-6.

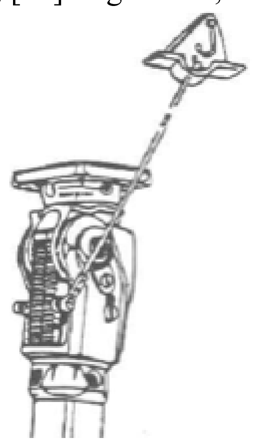


Figure 3-2 Locking Knee [46]

3.1.3 Stance Control Knee

This is the single axis constant friction knee having braking mechanism. To prevent the knee from buckling, when weight is applied on it while movement the braking mechanism is activated. The brake incorporated in this knee is friction based. To make this knee work again or amputee wants

Figure 3-3 Stance Control Knee (Otto Bock 3R49) [46]

to have sitting posture, he/she will need to unload the knee which will release the friction brake [29], [47]. Figure 3-3, 3-6.

3.1.4 Polycentric Knee

This type of knee is a four-bar mechanism, and it moves in sagittal plane. This knee collapse well during the swing phase. The collapsing feature allows the knee for easy change in position to sitting and is ideal for knee dis-articulation. The swing phase control can be either mechanical friction or hydraulic resistance [29], [47]. Figure 3-4, 3-6.

(a) (b)

Figure 3-5 Polycentric Knee (a) Medipro OP2 (b) Otto Bock 3R46 [46]

(a) (b)

Figure 3-4 Pneumatic/ Hydraulic Knee (a) Medipro OP4 (b) Ossur Total Knee [46]

3.1.5 Pneumatic/Hydraulic Knee

The hydraulic or pneumatic knee is an extension of single axis or polycentric knee, which consists of a cylinder containing valves which control the flow of hydraulics (fluid/air). These adjustable valves assist the amputees who walk in variable speed [29], [47]. Figure 3-5, 3-6.

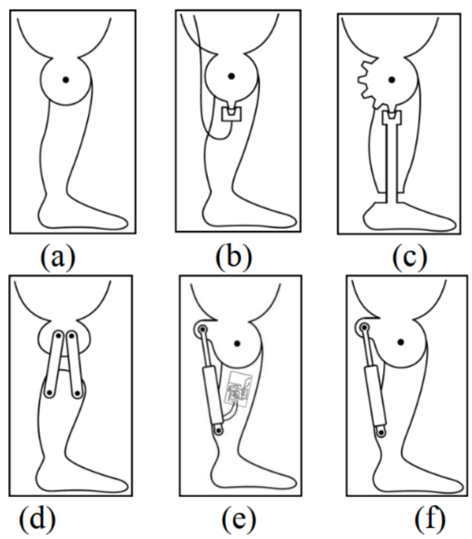


Figure 3-6 (a) Single Axis Knee (b) Locking Knee (c) Stance Control Knee (d) Polycentric Knee (e) Microprocessor Knee (f) Pneumatic Knee [29]

3.1.6 Microprocessor knee

This is the last type of prosthetic knee, which includes sensors (weight measuring and gyroscope/accelerometer). The data from these sensors is given as feedback to the microcontroller

Figure 3-7 Microprocessor Knee (a) Otto Bock C-Leg (b) Ossur Rheo (c) Freedom Pile [46]

which then controls the flexion/extension of knee joint. This system can be called as "enhanced hydraulic system", where the flow of hydraulic fluid is controlled by the opening and closing of valves which are operated via some actuator through microcontroller [29], [47], [48]. Figure 3-6, 3-7.

3.2 Design Considerations

Before building a mechanical design of controlling the damping of pneumatic knee joint there are few pre-requisites that need to be considered, such as:

- Suitable actuator
- Suitable material for manufacturing of designed mechanism

The mechanical design of the damping control mechanism is designed in SolidWorks®. In this section few of the considerations named above shall be discussed.

3.2.1 Actuator Choice

An important factor for choosing the actuator is that it should be smaller in size and lighter in weight. The actuators that are required here needs to be accurate and fast enough to reach desired position in minimum time. Due to these requirements usually stepper motors are used in prosthetics. Upon searching for such motors, it was found that Nema-11 motor would be a best fit in our case. The detail specs of Nema-11 motor are given in Table 3-1 and Figure 3-2.

Table 3-1 Nema-11 Stepper Motor Specs

Item	**Specification**
Rated Voltage	4.6 V
Current/Phase	0.67 A
Resistance/Phase	6.8 ohm
Inductance/Phase	4.9 mH
Holding Torque	950 g-cm
Number of Leads	4x
Rotor Inertia	12 g-cm^2
Weight	0.14 Kg
Length	44.5 mm

3.2.2 Material Choice

In most of the biomedical applications it is recommended to use such materials which are light in weight and relatively high strength. For designing the mechanism for controlling the damping in pneumatic knee joint Aluminum-6061 T6 has been chosen. The properties of this material are given in Table 3-3.

Table 3-2 Properties of Al-6061 T6

Sr. No.	Name of Property	Value
1	Density	2.70 g/cc
2	Tensile Strength (Yield)	276 MPa
3	Tensile Strength (Ultimate)	310 MPa
4	Modulus of Elasticity	68.9 GPa
5	Shear Modulus	26.0 GPa
6	Shear Strength	207 MPa

3.3 Part of Mechanism

The mechanism that has been designed consists of various parts. All these parts, along with their images are described below:

3.3.1 Flexion / Extension Gearbox Casing

This is the main housing (Figure 3-8) which holds all the spur gears and keeps the whole mechanism fixed on its position. The input and output of the gearbox is connected via this housing.

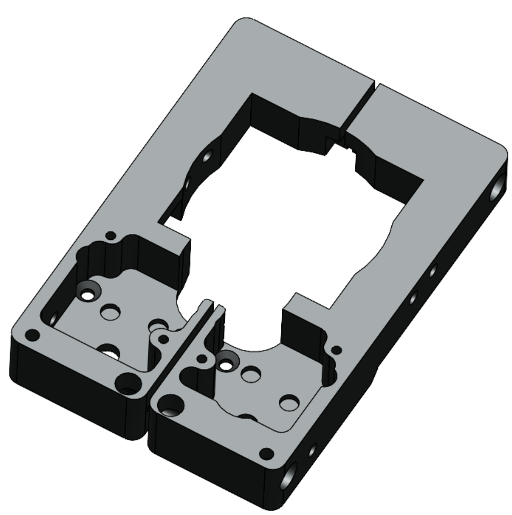


Figure 3-8 Gearbox Casing

Here the input is the shaft of stepper motor while the output is the L-key shaft (explained in section 3.3.8) which is connected to the damping control valve. The material of this part is Aluminum 6061 T6.

3.3.2 Flexion / Extension Gearbox Cover

This is the cover of the gearbox (Figure 3-9) which holds the spur gears in their meshing state. The gear shaft (type-II) is also mounted on this which acts as output of the system. The material of this part is Aluminum 6061 T6.

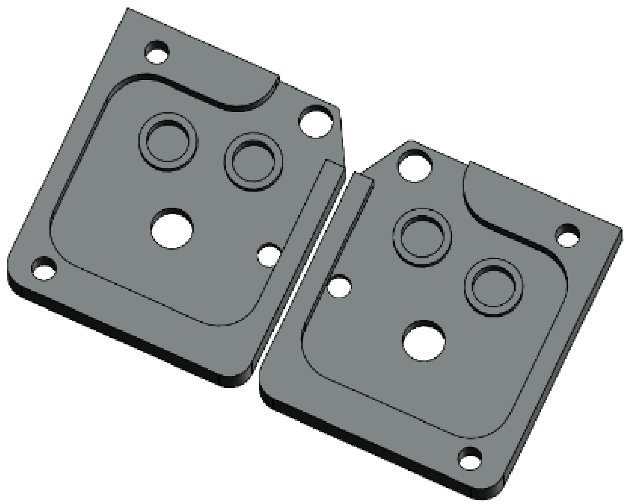


Figure 3-9 Gearbox Covers

3.3.3 Potentiometer Mount

This mount (Figure 3-10) serves two purposes. Firstly, it helps the mounting of potentiometers for connection with the stepper motors to measure accurate position of damping valve. Secondly, as there is just one mounting of the two halves (flexion gearbox, extension gearbox) on the gearbox

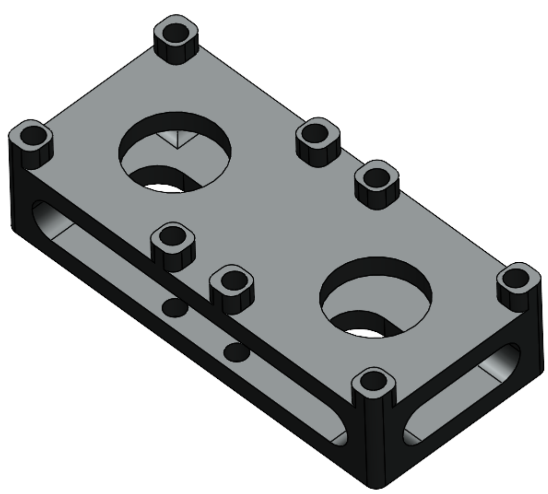


Figure 3-10 Potentiometer Mounting

casing so due to the weight of motors the lower part including the potentiometers bends inward causing the misalignment in the gear meshing and also cause extra load on stepper motor which in turns does not allow it to move freely, so this mount keeps the mechanism straight and does not cause the mentioned issues. The material of this part is Aluminum 6061 T6.

3.3.4 Spur Gear (Type-I)

There are two types of spur gears being used in this hardware. The type-I spur gear (Figure 3-11) is the large gear and they are six in number in total i.e., three in each gearbox casing. The table 3-4 shows the specs of this gear. The material of this part is Brass.

Table 3-3 Type-I Gear Specs

Module	0.25
Teeth	42
Pressure Angle	14.5°
Hub	One Sided
Shaft Diameter	5mm
Hub Diameter	9mm
Face Width	7mm

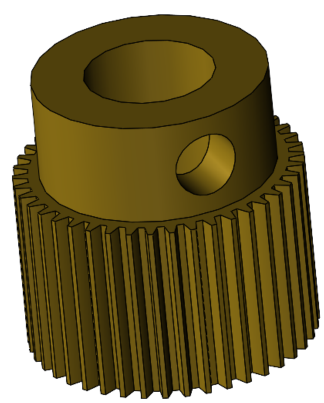


Figure 3-11 Type-I Gear

3.3.5 Gear Shaft (Type-I)

This is the shaft (Figure 3-12) on which the type-I gear is mounted. All the six type-I gears have same shaft. This shaft has a slot in it for adjusting the position of gear on it. The material of this part is Brass.

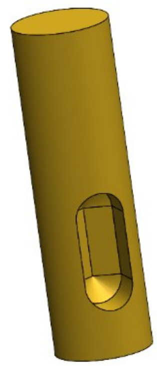


Figure 3-12 Gear Shaft type I

3.3.6 Spur Gear Type-II

This is the output gear (Figure 3-13) which is mounted on the output shaft of gearbox. Because of very small space available for this gear the gear has very small teeth and small diameter. The detail specs of this gear are given in table 3-5. The material of this part is Brass.

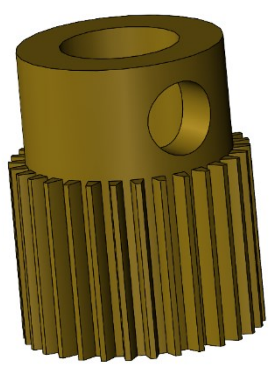


Figure 3-13 Type-II Gear

Table 3-4 Gear Type II Specs

Module	0.25
Teeth	30
Pressure Angle	14.5°
Hub	One Sided
Shaft Diameter	4mm
Hub Diameter	7mm
Face Width	6mm

3.3.7 Gear Shaft (Type-II)

On this shaft the output gear is mounted. This shaft (Figure 3-14) has an inner D-cut which helps in keeping the l-key shaft in line with the damping adjustment valve. From the top this shaft is mounted on the gearbox cover through the e-lock. The material of this shaft is Stainless Steel 304.

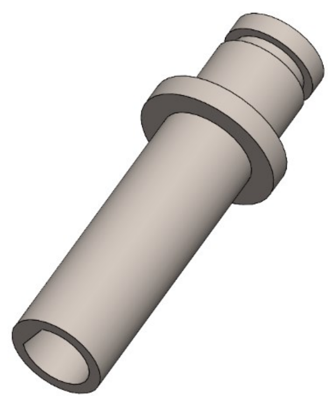


Figure 3-14 Gear Shaft Type-II

3.3.8 L-Key Shaft

The shaft (Figure 3-15) is coupled with the damping adjustment screw/valve. The size of hexagon of this shaft is of the size of M3. One size of this shaft has an outer D shape which is coupled with

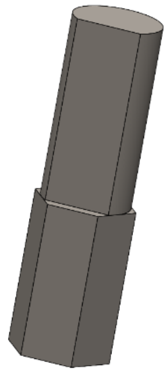


Figure 3-15 L-key Shaft

the ear shaft type-II. These two inner and outer D shapes slide (Figure 3-16) over each other while adjustment.

3.3.9 Potentiometers

There are two multi turn potentiometers used in this mechanism. Each of the potentiometer (Figure 3-18) is of the resistance of 10kohm and ten turn. Both are mounted directly with the shaft of stepper motor via a coupling.

Figure 3-16 Multi Turn Potentiometers

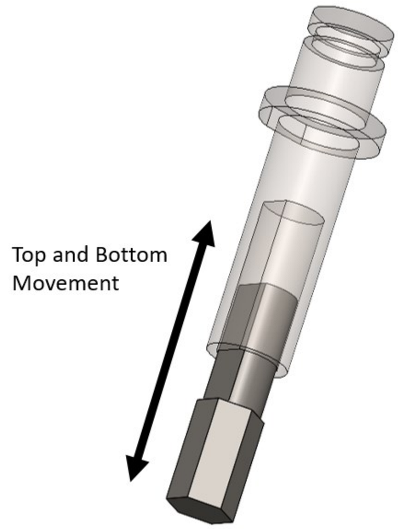


Figure 3-17 Sliding Movement

3.4 Damping Adjustment Mechanism

The pneumatic knee joint on which the mechanism was supposed to be designed is shown in Figure 1-2, and the damping valves need to be controlled are shown in Figure 1-3. The design of mechanism on this hardware was very critical as there is very little space available on the hardware

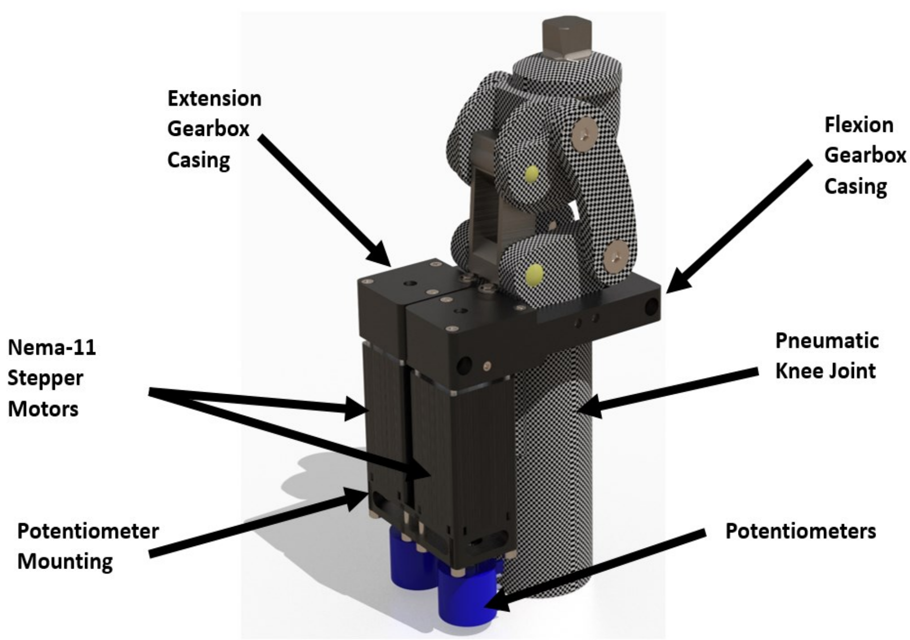


Figure 3-18 Mechanism Labelled Diagram

which could be used for adjustment of valves. A gear train mechanism has been used to control these valves. A total of four gears are used among which three have same specs while one has different specs. The designed mechanism is shown in Figure 3-18, which includes the pneumatic knee joint, stepper motors, flexion/extension gearbox casing, potentiometer mounting and potentiometers.

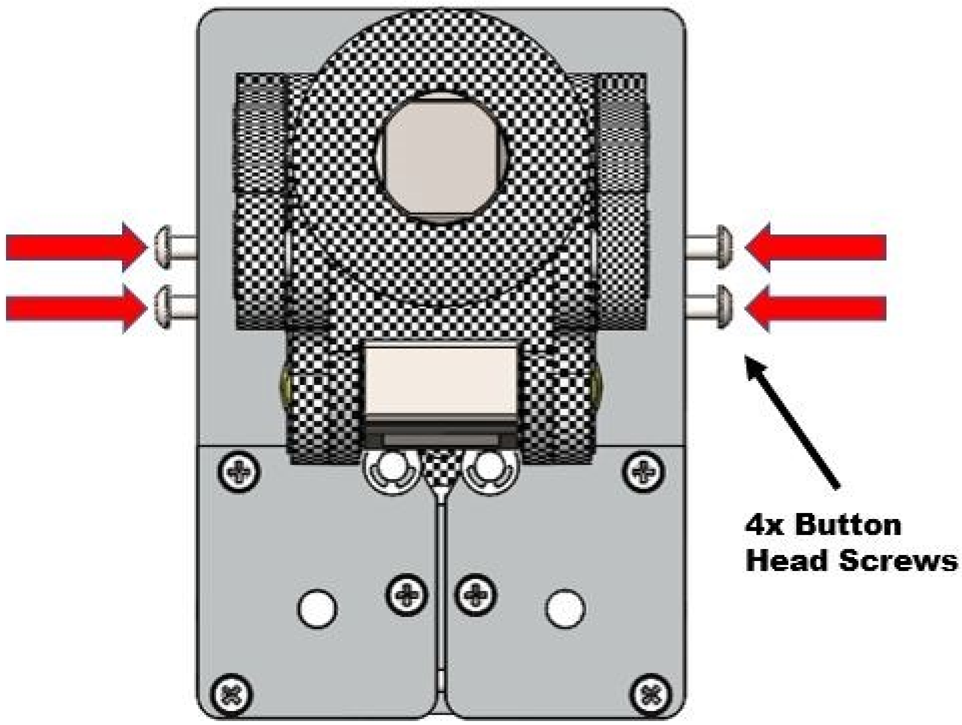


Figure 3-19 Mounting Screws

As seen in the Figure 3-19, both of these mounts i.e., flexion and extension, are mounted with the knee joint via four M3 button head screws. The two M3 button head screws, on each side, keep the mechanism intact with the knee joint from their respective sides, this can be seen in figure 3-20. For calculating the center distance of gear meshing following formulas have been used:

$$CD = \frac{[PD_1 + PD_2]}{2}$$

Here, CD is the center distance between the gears while PD is the pitch diameter of gear two meshing gears. To find the pitch diameter following formula has been used:

$$PD_x = \frac{NT_x * OD_x}{NT_x + 2}$$

Where, NT is the number of teeth, OD is the outer diameter of the gear and x is the number of gear i.e. 1, 2 for which pitch diameter is being calculated.

Chapter 4: Experimental Setup: Dataset Recording and Designed Mechanism

4.1 Experimental Setup for Dataset Recording

The hardware designed for recording of dataset as described in section 2.4.3 was used on 16 individuals for data recording. The mechanism for data recording is shown in Figure 4-1.

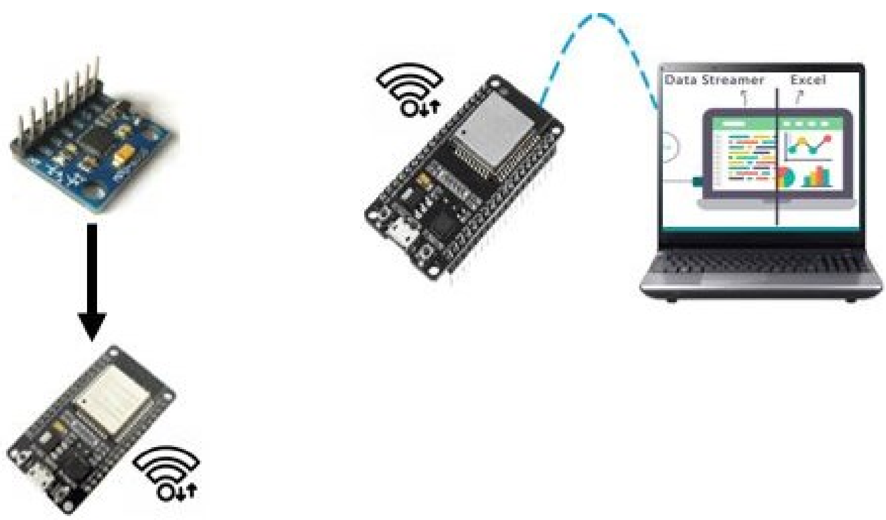


Figure 4-1 Data Recording Flow

The data is recorded in the three configurations as described in section 2.5, using the sensor hardware developed as shown in figure 2.13. The data is recorded from the inertial measurement unit (IMU). The IMU used here is MPU6050. This sensor includes 3-axis gyroscope, accelerometer, and magnetometer. The scale range of this gyroscope is ±250, ±500, ±1000 and ±2000 ◦/sec while that of accelerometer is ±2g, ±4g, ±8g and ±16g and both have 16-bit ADC. The scale of gyroscope and accelerometer used in this study is ±1000 and ±8g respectively.

Both accelerometer and gyroscope have been used for recording the dataset. The sensor modules are mounted on the limbs of body and the data from the IMU is read at the transmitter ESP32 module which is continuously transmitted to the receiver ESP32. This data is recorded on the data streamer add-in of Microsoft Excel. Later on, this data is saved as a CSV file. The data of both the IMUs is continuously received and recorded on the data streamer.

4.1.1 Calibration of IMU Sensor

It was found that the raw data received from the MPU6050 is not so stable and it shows large fluctuation of values while sending data to the receiver side. So, an algorithm has been developed which calculates the offset value for both the accelerometer and gyroscope by averaging 10k values for each sensor in all axes i.e., X, Y, Z.

(a) (b)

Figure 4-2 Location for (a) Walking, Jogging (b) Stair-up, Stair-down

4.1.2 Dataset Recording

In the process of dataset recording a total of sixteen (16) participants took part. The data has been recorded in the four modes of human activities:

1. Walking
2. Jogging

3. Stair-climbing up
4. Stair-climbing down

Table 4-1 Profiles of Participants

Subject No.	**Profile**			
	Gender	**Age**	**Height**	**Weight**
1	Male	30 years	188 cm	90 Kg
2	Male	21 years	172 cm	80 Kg
3	Male	19 years	180 cm	75 Kg
4	Male	24 years	175 cm	77 Kg
5	Male	26 years	177 cm	79 Kg
6	Male	28 years	170 cm	76 Kg
7	Male	28 years	190 cm	95 Kg
8	Male	31 years	167 cm	75 Kg
9	Male	31 years	178 cm	70 Kg
10	Male	31 years	183 cm	74 Kg
11	Male	24 years	173 cm	82 Kg
12	Male	24 years	160 cm	68 Kg
13	Male	26 years	175 cm	70 Kg
14	Male	29 years	170 cm	95 Kg
15	Male	27 years	170 cm	75 Kg
16	Male	24 years	171 cm	73 Kg

All the participants took part in recording all the four activities named above. The data of all the participants is recorded in the three configurations described in section 2.5. The data of walking and jogging is recorded in a plain passage Figure 4-2 (a). The distance of these two data recording modes is 150meters. The number of stairs for data recording is 8, while the image of stairs is shown in Figure 4-2 (b). While recording the data the sensors are mounted on the mid position of both upper and lower limbs. While testing, it was found that the data received from the sensor module has the initial position as the zero position. Due to this reason the IMU is always reset after fixing the module on the limb of participant. The profiles of the participants which took part in the data recording is given in Table 4-1.

All the participants were asked to perform the activities in their natural way of walking etc. due to this reason there is a variation of speed, moving styles and recording time of each participant. During the process of data recording, it was ensured that the position of sensor modules must be fixed, so that any inaccuracy in recording the data may be avoided due to lose sensor.

4.1.3 Pre-processing of Dataset

The data received from the sensor module to the receiver controller is in the form as shown in Figure 4-2. Here, the term "Id", shows the serial number of the sensor module i.e., sensor module #1 and sensor module #2, while Ax, Ay, Az, Gx, Gy, Gz followed by the Id shows the data of accelerometer and gyroscope respectively from that specific sensor module On the other hand the data standard i.e., WISDM, for the processing of algorithm needs to have the columns as described in Table 2-5.

Table 4-2 Recorded Dataset

A	B	C	D	E	F	G	H	I	J	K	L	M	N
Id: 1	Ax: 1225	Ay: -432	Az: 1413	Gx: -4	Gy: -5	Gz: -1	Id: 2	Ax: -29	Ay: 218	Az: 338	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1225	Ay: -432	Az: 1413	Gx: -4	Gy: -5	Gz: -1	Id: 2	Ax: -48	Ay: 181	Az: 339	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1253	Ay: -503	Az: 1447	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: -48	Ay: 181	Az: 339	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1253	Ay: -503	Az: 1447	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: -45	Ay: 123	Az: 342	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1268	Ay: -474	Az: 1455	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: -45	Ay: 123	Az: 342	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1268	Ay: -474	Az: 1455	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 7	Ay: 121	Az: 375	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1286	Ay: -435	Az: 1467	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 7	Ay: 121	Az: 375	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1286	Ay: -435	Az: 1467	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 32	Ay: 178	Az: 389	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1299	Ay: -390	Az: 1485	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 32	Ay: 178	Az: 389	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1299	Ay: -390	Az: 1485	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 58	Ay: 226	Az: 403	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1289	Ay: -308	Az: 1499	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 58	Ay: 226	Az: 403	Gx: 0	Gy: 0	Gz: 0

Id: 1	Ax: 1289	Ay: -308	Az: 1499	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 86	Ay: 247	Az: 426	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1283	Ay: -276	Az: 1495	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 86	Ay: 247	Az: 426	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1283	Ay: -276	Az: 1495	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 113	Ay: 263	Az: 438	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1286	Ay: -234	Az: 1478	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 113	Ay: 263	Az: 438	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1286	Ay: -234	Az: 1478	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 148	Ay: 305	Az: 455	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1285	Ay: -207	Az: 1454	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 148	Ay: 305	Az: 455	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1285	Ay: -207	Az: 1454	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 156	Ay: 311	Az: 452	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1281	Ay: -196	Az: 1436	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 156	Ay: 311	Az: 452	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1281	Ay: -196	Az: 1436	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 150	Ay: 295	Az: 446	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1272	Ay: -176	Az: 1417	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 150	Ay: 295	Az: 446	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1272	Ay: -176	Az: 1417	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 139	Ay: 267	Az: 434	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1277	Ay: -185	Az: 1423	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 139	Ay: 267	Az: 434	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1277	Ay: -185	Az: 1423	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 121	Ay: 198	Az: 426	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1285	Ay: -210	Az: 1443	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 121	Ay: 198	Az: 426	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1285	Ay: -210	Az: 1443	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 113	Ay: 156	Az: 417	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1300	Ay: -237	Az: 1456	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 113	Ay: 156	Az: 417	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1300	Ay: -237	Az: 1456	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 100	Ay: 118	Az: 403	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1326	Ay: -311	Az: 1447	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 100	Ay: 118	Az: 403	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1326	Ay: -311	Az: 1447	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 83	Ay: 88	Az: 396	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1332	Ay: -348	Az: 1429	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 83	Ay: 88	Az: 396	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1332	Ay: -348	Az: 1429	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 38	Ay: 24	Az: 364	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1328	Ay: -391	Az: 1428	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 38	Ay: 24	Az: 364	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1328	Ay: -391	Az: 1428	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 25	Ay: -2	Az: 339	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1333	Ay: -433	Az: 1425	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 25	Ay: -2	Az: 339	Gx: 0	Gy: 0	Gz: 0
Id: 1	Ax: 1333	Ay: -433	Az: 1425	Gx: -4	Gy: -6	Gz: -1	Id: 2	Ax: 22	Ay: -14	Az: 316	Gx: 0	Gy: 0	Gz: 0

All this data needs to be in the form that the sequence of all the columns must be the field name of Table 2.5. All this data needs to be checked to eliminate all the garbage value being recorded so that we have accurate data to train the algorithm. Finally, the pre-processed data can be seen in Table 4-3. In the Table 4-2 the Column-A shows the Id of the subject i.e., 1, 2, 3 etc., while Column-B shows the activity code i.e., Walking, Jogging etc. and Column-C through H shows the value of accelerometer and gyroscope respectively 3 columns each of sensor module-1 and Column-I through N shows the value of accelerometer and gyroscope respectively 3 columns each of sensor module-2. The graphical view of few data from accelerometer and gyroscope can be seen in Section 5.1.

Table 4-3 Pre-Processed Data

A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	walk	62	2564	4118	18	-2	-55	-1936	-1652	1198	2	-11	11
1	walk	62	2564	4118	18	-2	-55	-1934	-1402	1190	2	-11	12
1	walk	558	2948	3482	18	-2	-55	-1934	-1402	1190	2	-11	12
1	walk	558	2948	3482	18	-2	-55	-1609	-966	1104	1	-12	13
1	walk	558	2948	3482	18	-2	-55	-1081	-503	933	0	-12	14
1	walk	2294	3612	2113	19	-1	-55	-1081	-503	933	0	-12	14
1	walk	2294	3612	2113	19	-1	-55	-554	-191	750	0	-12	15
1	walk	3085	3666	1558	20	-1	-54	-554	-191	750	0	-12	15
1	walk	3772	3592	958	20	0	-54	-554	-191	750	0	-12	15
1	walk	3772	3592	958	20	0	-54	229	-39	400	-1	-13	17
1	walk	4258	3532	407	21	0	-53	229	-39	400	-1	-13	17
1	walk	4258	3532	407	21	0	-53	407	-91	247	-2	-13	18
1	walk	4571	3505	-22	21	0	-52	407	-91	247	-2	-13	18
1	walk	4571	3505	-22	21	0	-52	546	-171	145	-3	-13	18
1	walk	4571	3505	-22	21	0	-52	686	-222	62	-4	-14	19
1	walk	4828	3347	-528	22	-1	-50	686	-222	62	-4	-14	19
1	walk	5044	3049	-699	21	-1	-48	686	-222	62	-4	-14	19
1	walk	5044	3049	-699	21	-1	-48	1014	-84	-41	-6	-14	21
1	walk	5216	2682	-939	21	-1	-47	1014	-84	-41	-6	-14	21
1	walk	5216	2682	-939	21	-1	-47	1248	20	-90	-7	-14	21
1	walk	5199	2333	-1046	20	-2	-45	1248	20	-90	-7	-14	21
1	walk	5199	2333	-1046	20	-2	-45	1528	169	-146	-9	-14	21
1	walk	5199	2333	-1046	20	-2	-45	1886	354	-243	-10	-14	22
1	walk	4571	1815	-777	17	-2	-42	1886	354	-243	-10	-14	22
1	walk	4153	1621	-540	16	-3	-40	1886	354	-243	-10	-14	22
1	walk	4153	1621	-540	16	-3	-40	2744	932	-576	-13	-14	22

1	walk	3654	1563	-347	15	-3	-38	2744	932	-576	-13	-14	22
1	walk	3654	1563	-347	15	-3	-38	3089	1160	-827	-15	-14	22
1	walk	3080	1563	-135	13	-4	-36	3089	1160	-827	-15	-14	22
1	walk	3080	1563	-135	13	-4	-36	3333	1375	-1105	-16	-14	23
1	walk	2515	1602	149	12	-4	-34	3333	1375	-1105	-16	-14	23
1	walk	2515	1602	149	12	-4	-34	3530	1595	-1415	-17	-13	23
1	walk	2515	1602	149	12	-4	-34	3739	1796	-1772	-18	-13	24
1	walk	1729	1878	515	11	-5	-29	3739	1796	-1772	-18	-13	24
1	walk	1540	1988	514	10	-6	-27	3739	1796	-1772	-18	-13	24
1	walk	1540	1988	514	10	-6	-27	4246	2012	-2423	-19	-13	25
1	walk	1405	1993	411	9	-7	-24	4246	2012	-2423	-19	-13	25
1	walk	1405	1993	411	9	-7	-24	4422	2026	-2657	-19	-12	25
1	walk	1266	1880	296	9	-7	-21	4422	2026	-2657	-19	-12	25
1	walk	1266	1880	296	9	-7	-21	4551	1939	-2925	-19	-12	26

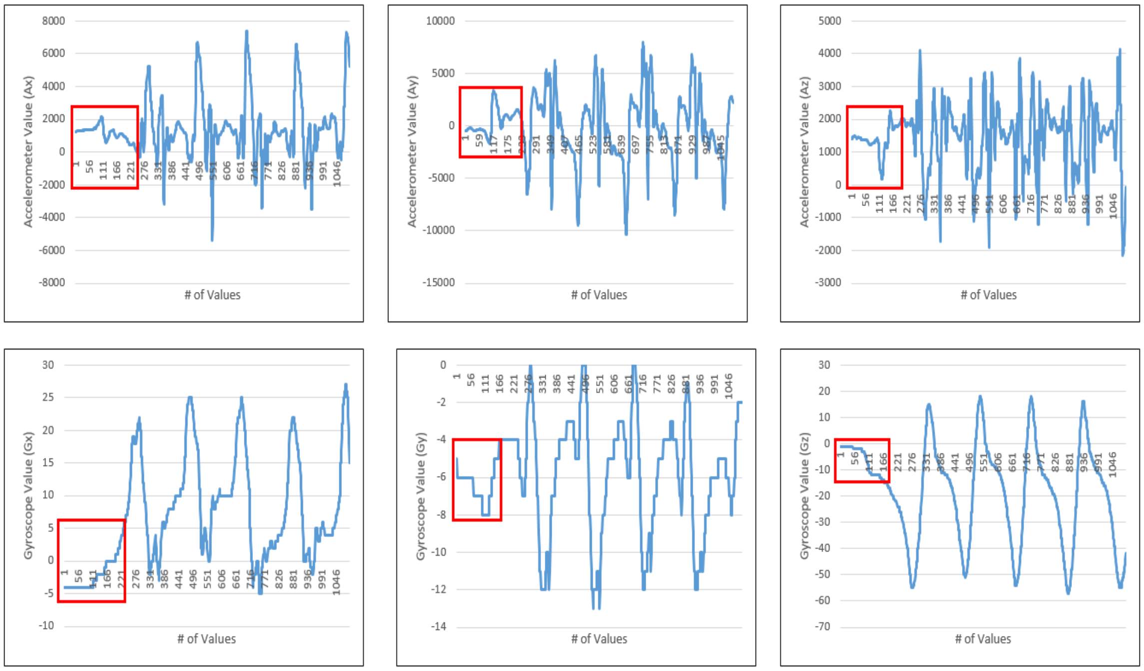


Figure 4-3 Garbage Values in Recorded Data

The data shown in the red boxes in the Figure 4-3, is the garbage data which needs to be discarded while pre-processing of data. This is the data, which is recorded when the recording has started, and no activity is taking place. Usually, this type of data can be seen either in the start of activity or in the end of activity. This needs to be discarded because

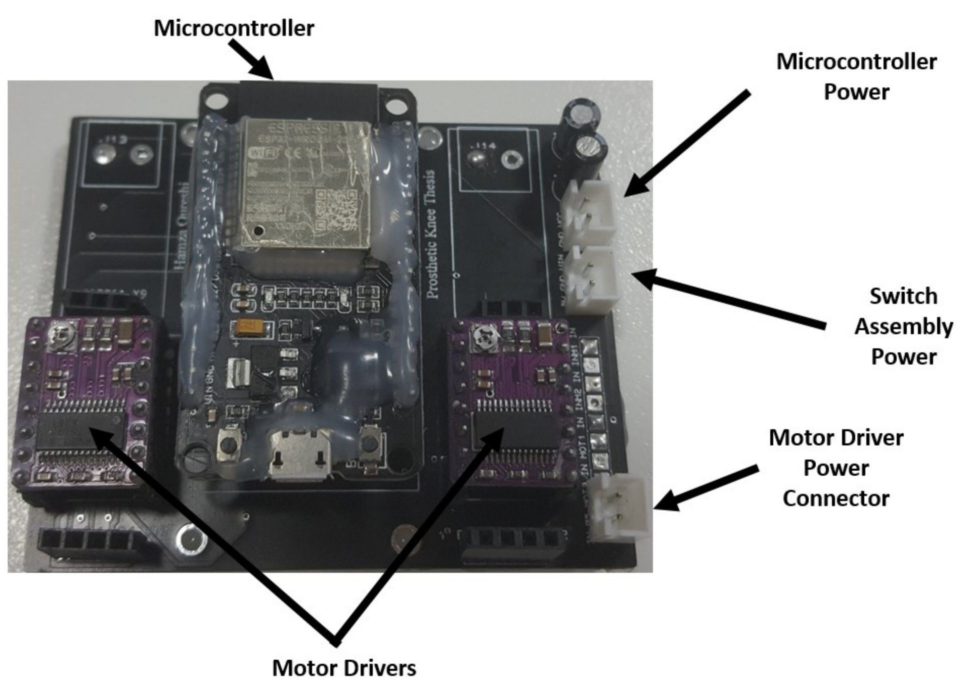


Figure 4-4 Motor Driver PCB with MCU

it can cause some anomaly while training of algorithm. Such useless data effects the weights of the machine learning / artificial intelligence algorithm which in turn results in the wrong recognition of features during the use of algorithm in field. In our case, such data may cause knee joint to have some irrelevant setting causing the amputee in unstable movement.

4.2 Experimental Setup for Mechanism Testing

The mechanical mechanism that has been designed as explained in section 3.3, has been tested using manual configurations of switch board. A motor driver board was designed

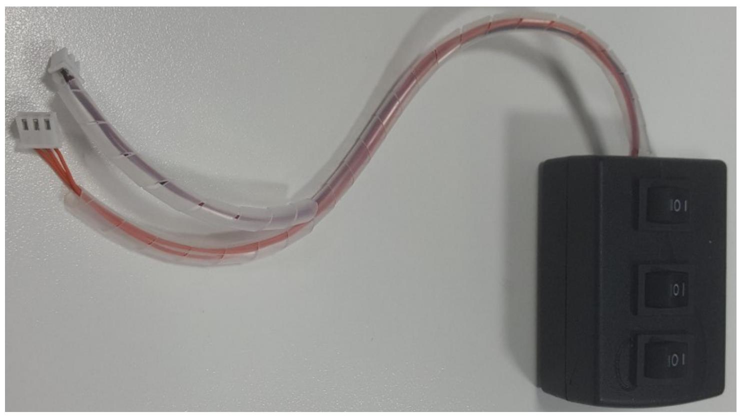


Figure 4-6 Switch Assembly

which reads the position from potentiometer and then moves to the required setting using switch board. For making the mechanism work the hardware being used is shown in Figure 4-5, 4-6, 4-7. In the scope of this thesis, the mechanism design needs to test using the switch assembly. The flowchart for working of this mechanism test is shown in Figure 4-8.

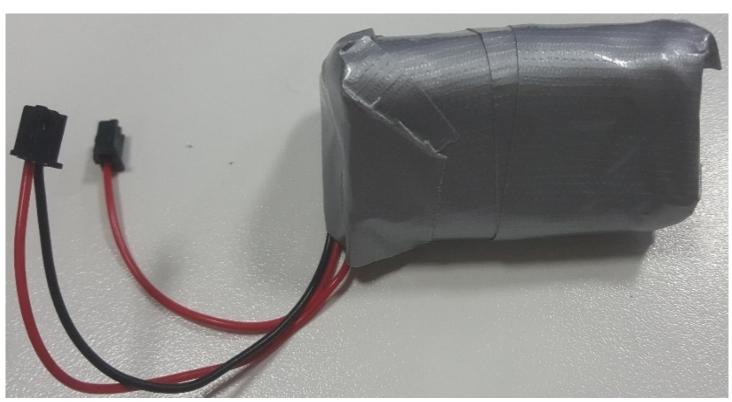


Figure 4-5 Battery Pack

As shown in the flowchart Figure 4-14, when the system is turned ON initially the input from the potentiometer is read by microcontroller. And both the flexion and extension damping are set to the default position. As soon as the state of switch is changed from the default position to walking position, the flexion and extension damping is set to that position, and the same process repeats for all the configurations. The states of the switch assembly are defined in table 4-2. In Figure 4-12, the switch on the top is the SW-1 and the one in the middle is SW-II while the switch on the bottom is SW-III.

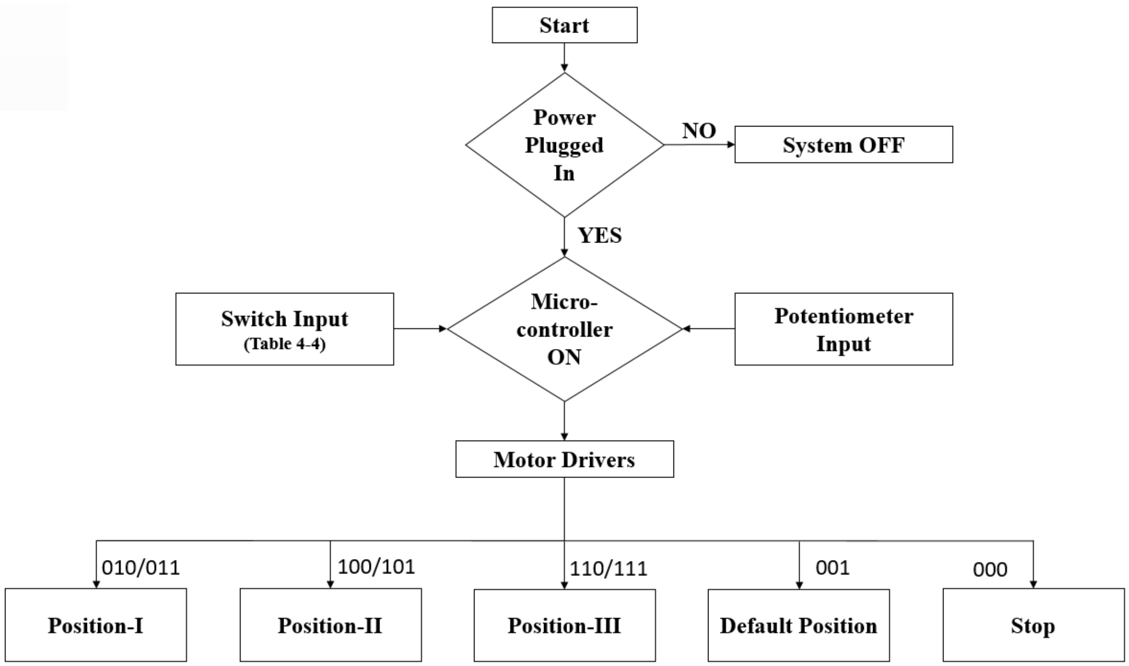


Figure 4-7 Flow Chart

Table 4-4 States of Switch Assembly

INPUT			OUTPUT
SW-I	**SW-II**	**SW-III**	**O/P State**
0	0	0	Stop (keep current position)
0	1	0	Position-I
1	0	0	Position-II
1	1	0	Position-III
0	0	1	Default Position/ Home Position
0	1	1	Position-I
1	0	1	Position-II
1	1	1	Position-III

Chapter 5: Results, Conclusion & Future Recommendations

5.1 Results & Conclusion

The dataset recorded from the hardware designed (section 2.4.3, 4.1), has given the results as shown in the Figure 5-1 through 5-6. The periodicity of the data can clearly be seen in this result. If we compare this result with literature [11], [49] it can be said that the results are very close to ideal results. This periodicity in the results shows the ADL in series. The data recorded in three configurations shows the gait pattern of ADL in walking, jogging, stair-up, and stair-down. All this data will be used to differentiate the difference of activity recorded on different body positions. The results also show that the hardware designed for data recording is efficient enough to record the best possible data with negligible error.

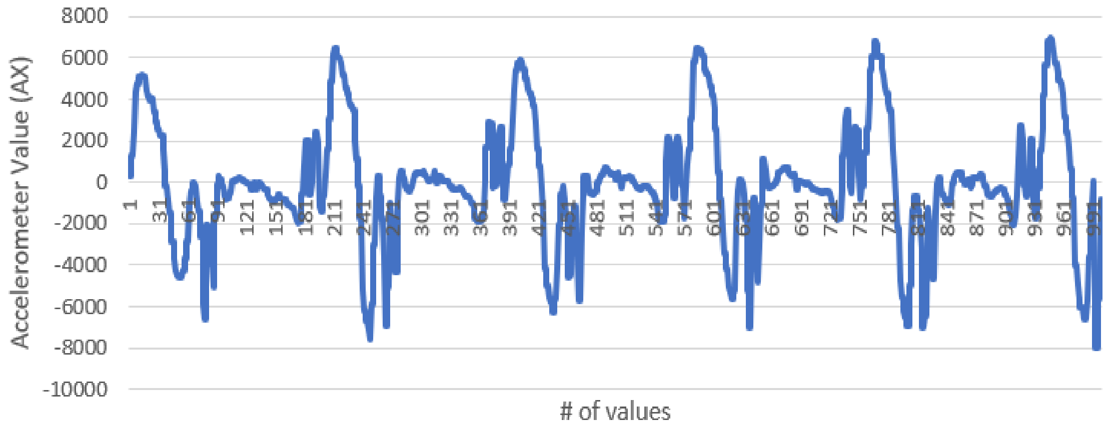


Figure 5-1 Accelerometer Ax

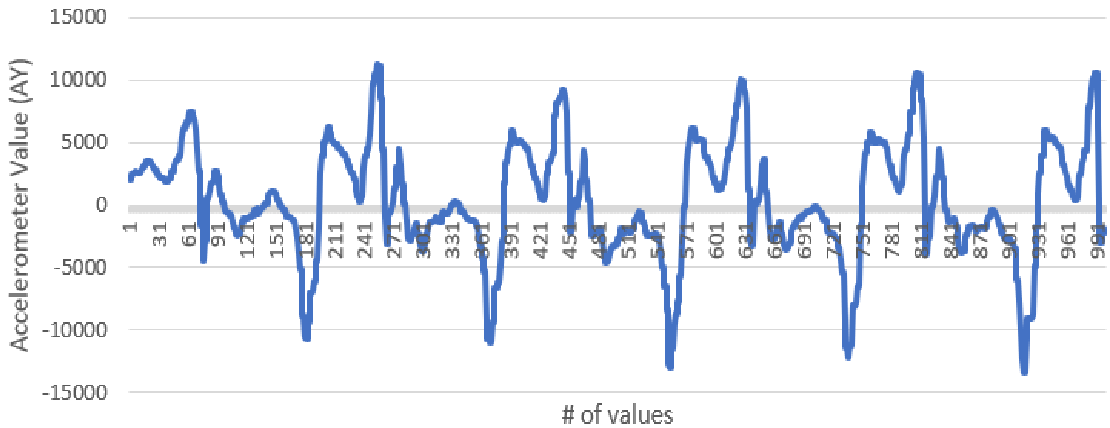


Figure 5-2 Accelerometer Ay

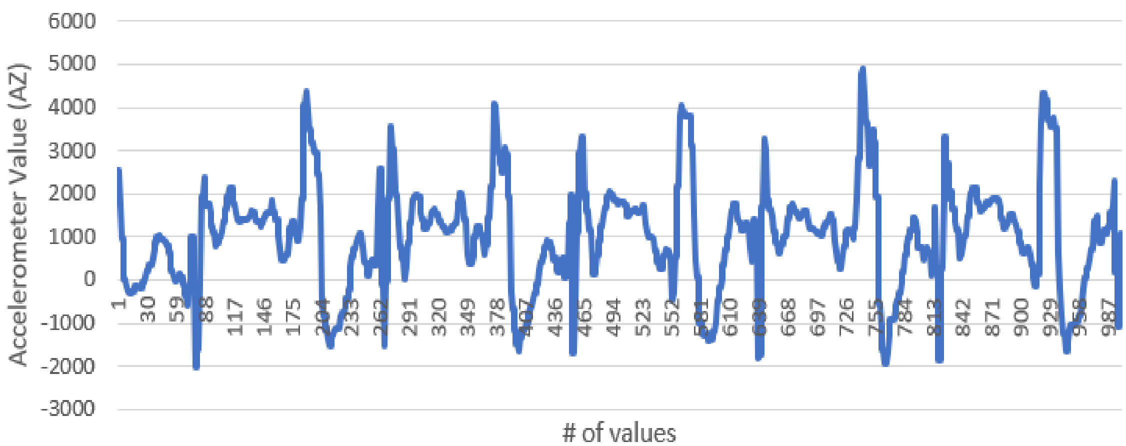


Figure 5-3 Accelerometer Az

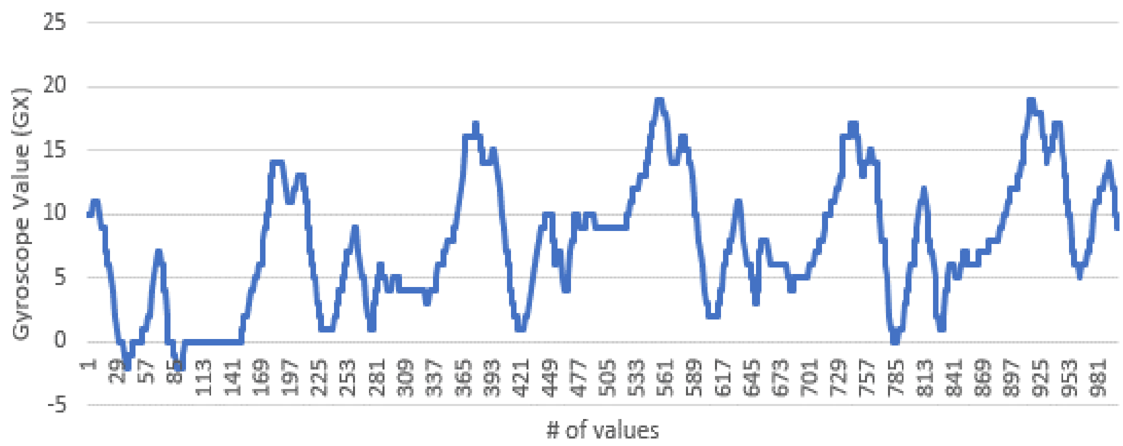


Figure 5-4 Gyroscope Gx

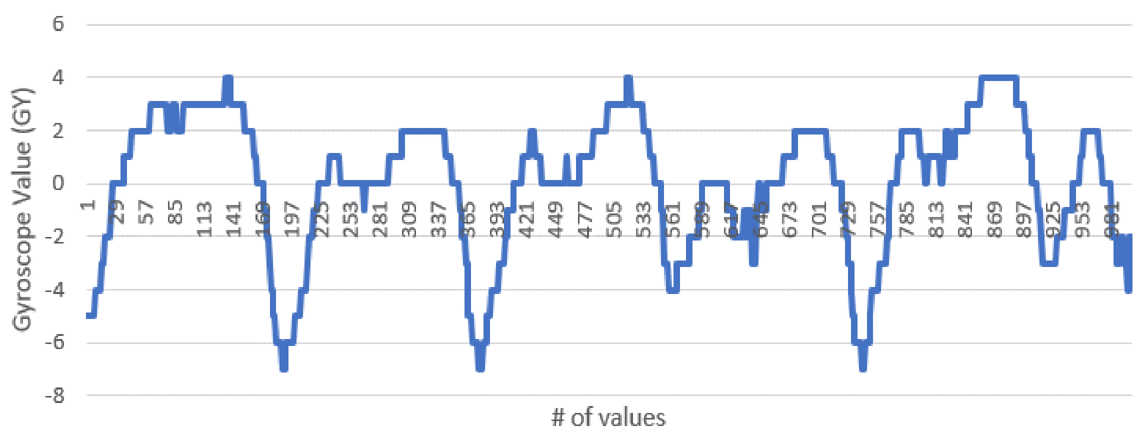


Figure 5-5 Gyroscope Gy

Figure 5-6 Gyroscope Gz

The Figures 5-7 shows the number of data values recorded in different modes. There are four major divisions which shows the data of walking, jogging, stair-up, stair-down, and the three bars in each division shows the values of data while mounting the sensor on the three configurations (section 2.5).

The Figure 5-8 shows the graphical view of all four ADLs recorded. The difference in the frequencies and the amplitudes shows the walking speed and movement of limbs during activity performance.

The damping adjustment mechanism (section 3.4) has been tested, at this stage, using selection switch assembly. Three positions (table 4-4) have been used for testing the hardware. It has been found that the response time of the hardware varies from 600ms to 1800ms to switch from one position to another position based on the difference of damping required.

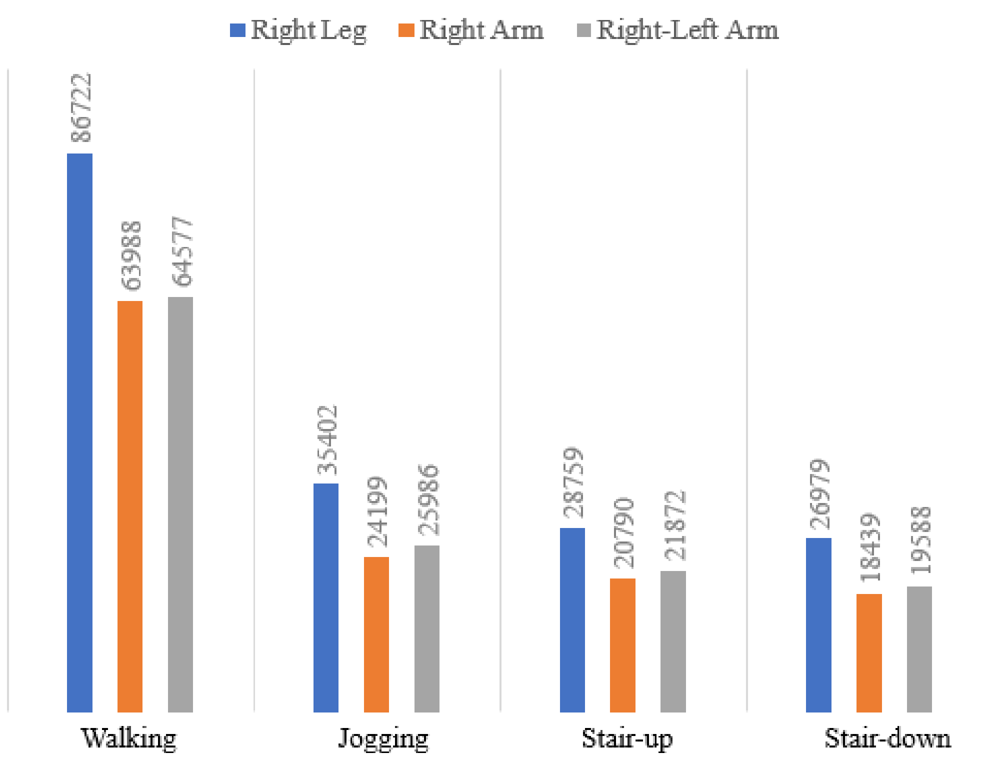


Figure 5-7 Number of data points for all configurations

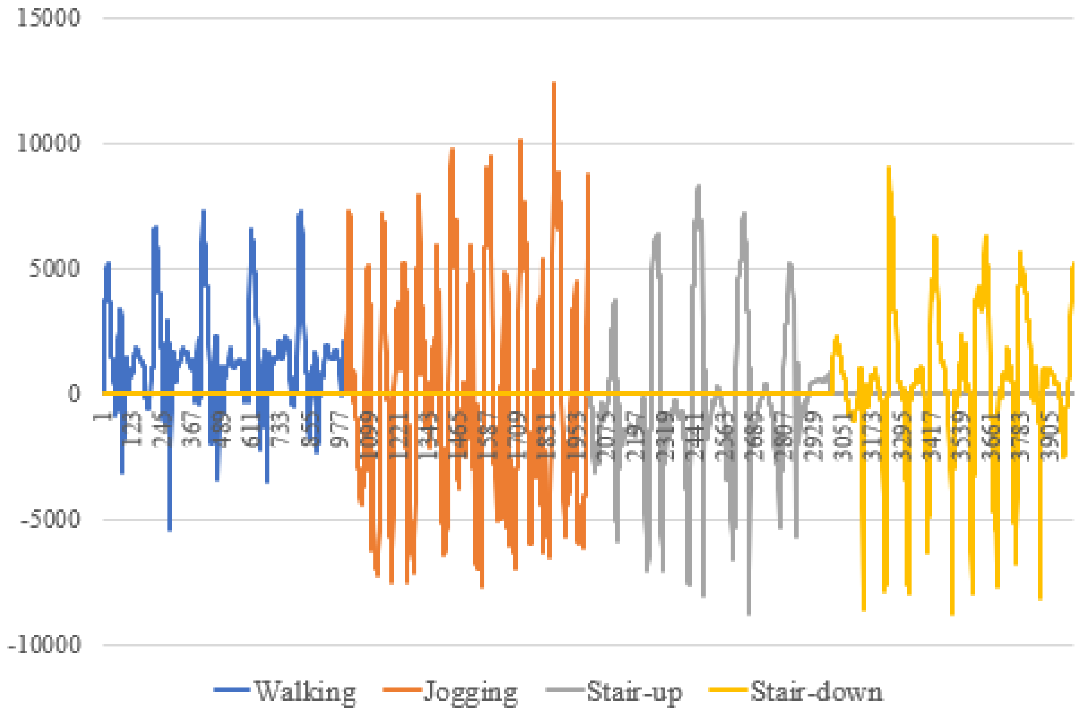


Figure 5-8 Brief graphical view of ADLs recorded

Based on the analysis of data recorded, It has been found that the gait cycle of walking is completed in 1.4 seconds while the rate is data recording is 140Hz. The time required to change the state of prosthesis varies from 0.6 sec to 1.8 sec (Figure 5-9). The Figures 5-11 and 5-12, shows the graphical representation of the time required to change the state.

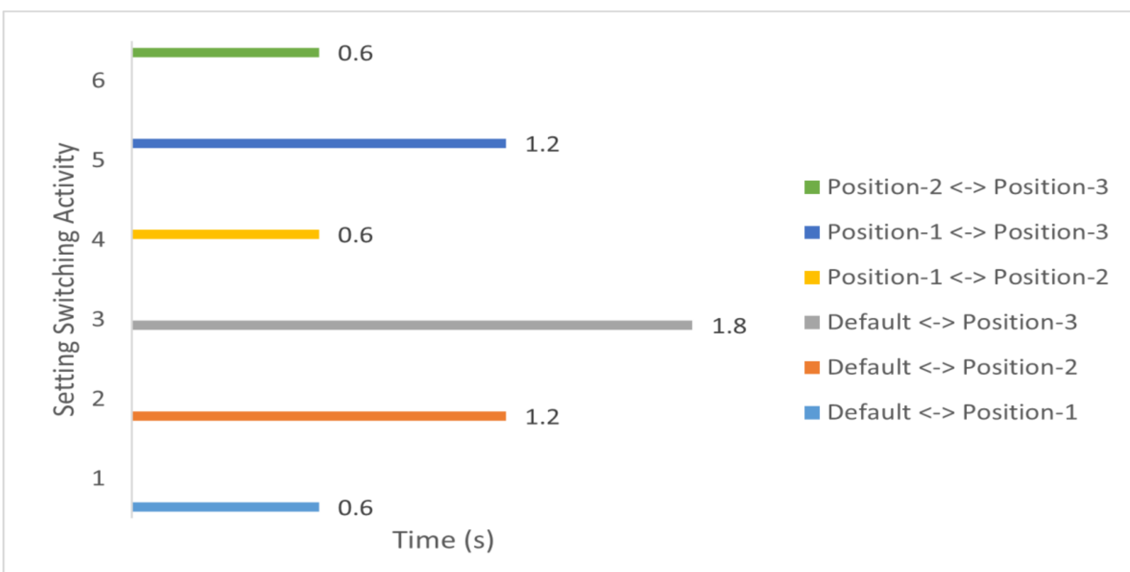


Figure 5-9 Time graph for switching activity

One green vertical column shows the time span of 0.3 sec, so min two highlighted columns are showing the state change in 0.6 sec while the six vertical columns show the time required to be 1.8 sec. the graph in figure 5-10, shows the one division of one gait cycle in swing and stance phase against the time and percentage. From literature [50] it has been found that the swing phase is the 60% of a gait cycle while the stance phase is the 40% of gait cycle. In the graph shown in Figure the gait cycle of walking is shown which shows that it completes in 1.5 seconds. So, it can be said that there is the switching state, in same gait cycle, can be achieved to the new state if it is activated in the early stages of swing phase and it is the consecutive state of the current state otherwise it will be achieved in the coming gait cycle.

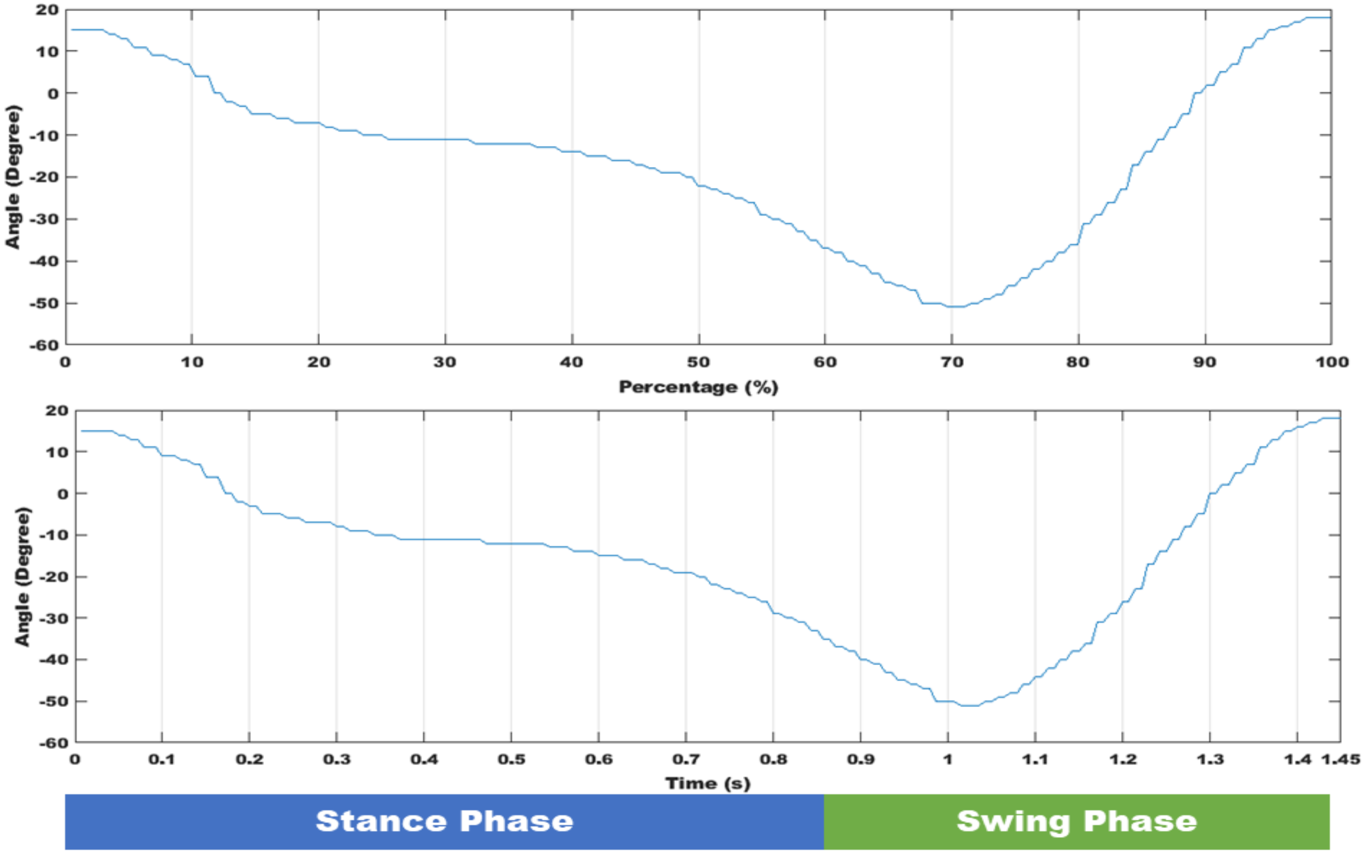


Figure 5-10 One Gait Cycle

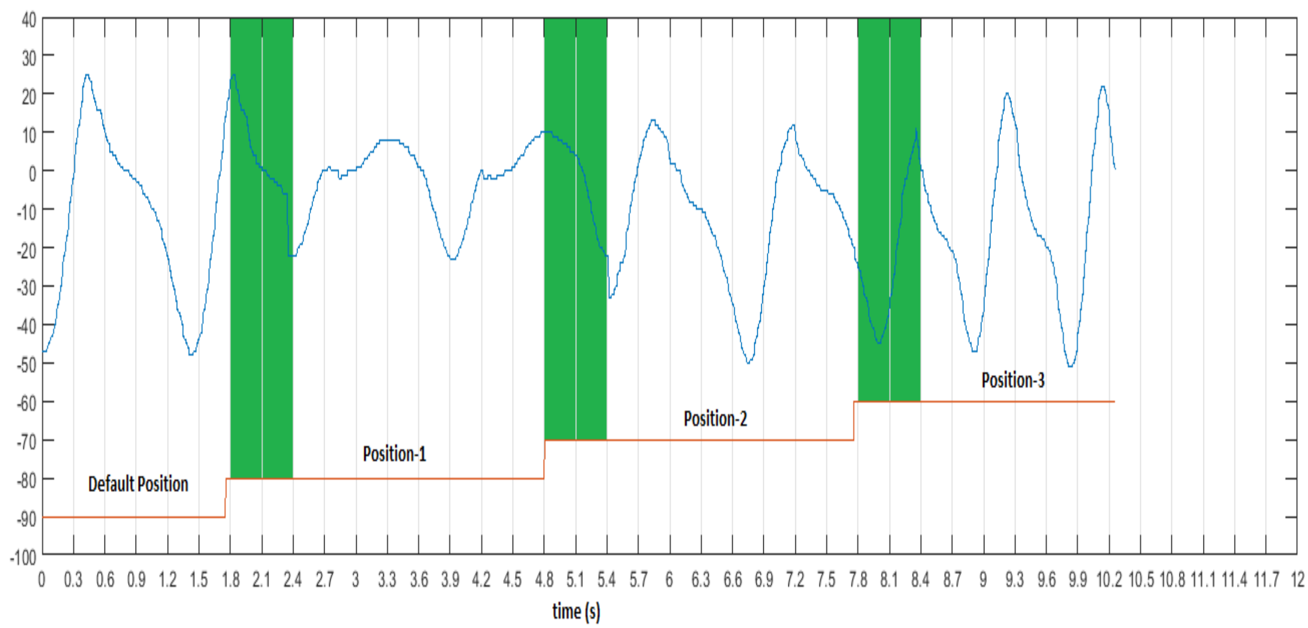


Figure 5-11 Graphical Representation of State Change Stepwise

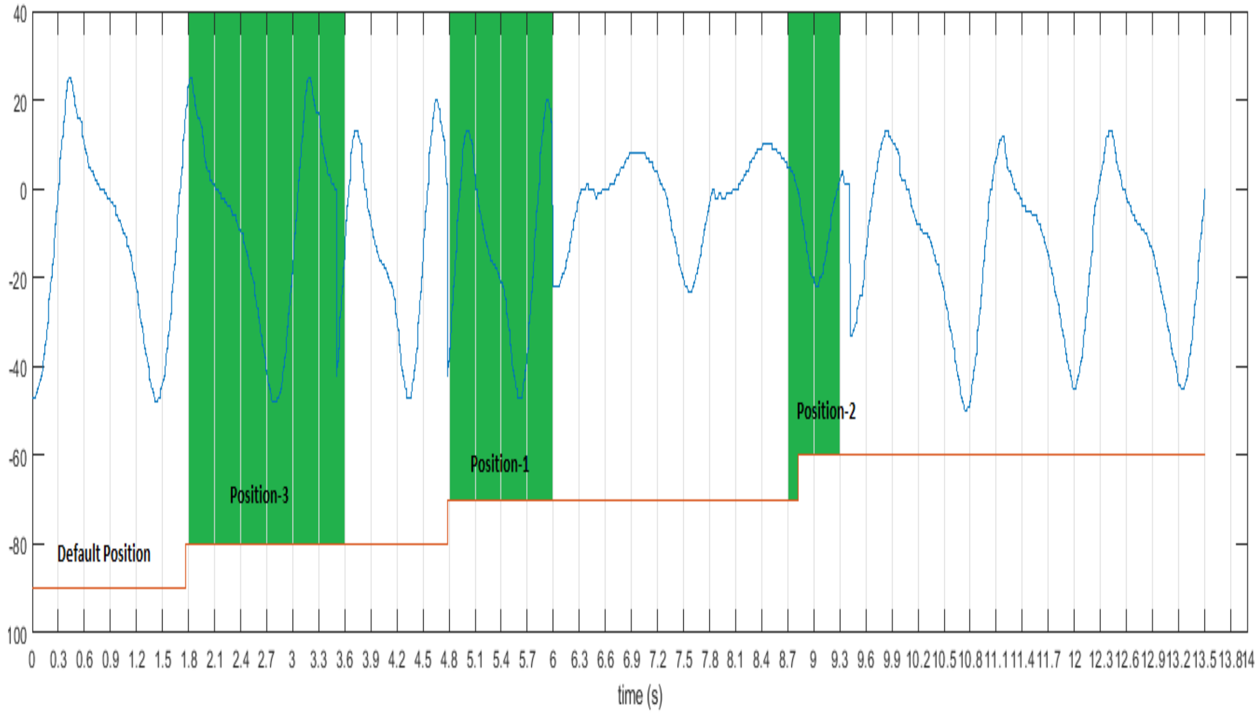


Figure 5-12 Graphical Representation of State Change Randomly

5.2 Future Recommendations

As this research comprises of two phases i.e., dataset recording hardware and damping control of pneumatic knee joint. In both these systems designed and tested as explained in chap 3 and chap 4, following improvements have been found to be worked upon in future:

- During the testing of hardware, it has been found that the hardware designed may be improved in terms of making just one PCB, as in our hardware the microcontroller and the gyroscope are two different modules mounted on one PCB. But in future it is recommended that the discrete components on a unit printed circuit board.

- The new PCB must have such an enclosure, along with stretchable Velcro straps, which should be easily mountable on the body to record data.

- In this research the stepper motors are used in mechanical design, it is recommended to use some such stepper/dc motors which are more in weight.

- The multi turn potentiometers are used for remembering of home position to help in reaching the desired position easily and accurately, it is recommended to use absolute encoders.

- The design of pneumatic knee joint needs some alteration for easy access of damping control valves to help in easy meshing of spur gears, in the current system the meshing of spur gear type-II (section 3.3.6) cause meshing problem.

Chapter 6: Bibliography

[1] R. S. Antunes *et al.*, “A Survey of Sensors in Healthcare Workflow Monitoring,” *ACM Comput. Surv.*, vol. 51, no. 2, pp. 1–37, Mar. 2019, doi: 10.1145/3177852.

[2] K. Altun and B. Barshan, “Human Activity Recognition Using Inertial/Magnetic Sensor Units,” in *Human Behavior Understanding*, vol. 6219, A. A. Salah, T. Gevers, N. Sebe, and A. Vinciarelli, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 38–51. doi: 10.1007/978-3-642-14715-9_5.

[3] Y.-J. Hong, I.-J. Kim, S. C. Ahn, and H.-G. Kim, “Activity Recognition Using Wearable Sensors for Elder Care,” in *2008 Second International Conference on Future Generation Communication and Networking*, Hainan, China, Dec. 2008, pp. 302–305. doi: 10.1109/FGCN.2008.165.

[4] F. Demrozi, G. Pravadelli, A. Bihorac, and P. Rashidi, “Human Activity Recognition using Inertial, Physiological and Environmental Sensors: a Comprehensive Survey,” *IEEE Access*, vol. 8, pp. 210816–210836, 2020, doi: 10.1109/ACCESS.2020.3037715.

[5] A. Mai and S. Commuri, “Gait identification for an intelligent prosthetic foot,” in *2011 IEEE International Symposium on Intelligent Control*, Denver, CO, USA, Sep. 2011, pp. 1341–1346. doi: 10.1109/ISIC.2011.6045418.

[6] “World Report on Disability,” p. 350.

[7] I. Handzic and K. B. Reed, “Recognition of gait impairment evaluated using an artificial gait stimuli,” in *2015 IEEE International Conference on Rehabilitation Robotics (ICORR)*, Singapore, Singapore, Aug. 2015, pp. 1008–1013. doi: 10.1109/ICORR.2015.7281336.

[8] M. I. Awad *et al.*, “Towards a Smart Semi-Active Prosthetic Leg: Preliminary Assessment and Testing,” *IFAC-PapersOnLine*, vol. 49, no. 21, pp. 170–176, 2016, doi: 10.1016/j.ifacol.2016.10.539.

[9] “Senthil Selvam et al. - 2021 - Prosthetics for Lower Limb Amputation.pdf.”

[10] M. Windrich, M. Grimmer, O. Christ, S. Rinderknecht, and P. Beckerle, “Active lower limb prosthetics: a systematic review of design issues and solutions,” *BioMed Eng OnLine*, vol. 15, no. S3, p. 140, Dec. 2016, doi: 10.1186/s12938-016-0284-9.

[11] O. S. Ajani and H. El-Hussieny, “An ANFIS-based Human Activity Recognition using IMU sensor Fusion,” in *2019 Novel Intelligent and Leading Emerging Sciences Conference (NILES)*, Giza, Egypt, Oct. 2019, pp. 34–37. doi: 10.1109/NILES.2019.8909289.

[12] R. Chavarriaga *et al.*, “The Opportunity challenge: A benchmark database for on-body sensor-based activity recognition,” *Pattern Recognition Letters*, vol. 34, no. 15, pp. 2033–2042, Nov. 2013, doi: 10.1016/j.patrec.2012.12.014.

[13] A. Calatroni, D. Roggen, and G. Troster, “Collection and curation of a large reference dataset for activity recognition,” in *2011 IEEE International Conference on Systems, Man, and Cybernetics*, Anchorage, AK, USA, Oct. 2011, pp. 30–35. doi: 10.1109/ICSMC.2011.6083638.

[14] D. Roggen *et al.*, “Collecting complex activity datasets in highly rich networked sensor environments,” in *2010 Seventh International Conference on Networked Sensing Systems (INSS)*, Kassel, Germany, Jun. 2010, pp. 233–240. doi: 10.1109/INSS.2010.5573462.

[15] J. A. Ward, P. Lukowicz, and H. W. Gellersen, “Performance metrics for activity recognition,” *ACM Trans. Intell. Syst. Technol.*, vol. 2, no. 1, pp. 1–23, Jan. 2011, doi: 10.1145/1889681.1889687.

[16] K. Altun and B. Barshan, “Human Activity Recognition Using Inertial/Magnetic Sensor Units,” in *Human Behavior Understanding*, vol. 6219, A. A. Salah, T. Gevers, N. Sebe, and A. Vinciarelli, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 38–51. doi: 10.1007/978-3-642-14715-9_5.

[17] W. Kong *et al.*, “Development of a real-time IMU-based motion capture system for gait rehabilitation,” in *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, Shenzhen, China, Dec. 2013, pp. 2100–2105. doi: 10.1109/ROBIO.2013.6739779.

[18] C.-T. Yen, J.-X. Liao, and Y.-K. Huang, “Human Daily Activity Recognition Performed Using Wearable Inertial Sensors Combined With Deep Learning Algorithms,” *IEEE Access*, vol. 8, pp. 174105–174114, 2020, doi: 10.1109/ACCESS.2020.3025938.

[19] S. Chung, J. Lim, K. J. Noh, G. Kim, and H. Jeong, “Sensor Data Acquisition and Multimodal Sensor Fusion for Human Activity Recognition Using Deep Learning,” *Sensors*, vol. 19, no. 7, p. 1716, Apr. 2019, doi: 10.3390/s19071716.

[20] M. Kyrarini, X. Wang, and A. Graser, “Comparison of vision-based and sensor-based systems for joint angle gait analysis,” in *2015 IEEE International Symposium on Medical Measurements and Applications (MeMeA) Proceedings*, Torino, Italy, May 2015, pp. 375–379. doi: 10.1109/MeMeA.2015.7145231.

[21] Y. Wang, S. Cang, and H. Yu, “A survey on wearable sensor modality centred human activity recognition in health care,” *Expert Systems with Applications*, vol. 137, pp. 167–190, Dec. 2019, doi: 10.1016/j.eswa.2019.04.057.

[22] A. Bulling, U. Blanke, and B. Schiele, “A tutorial on human activity recognition using body-worn inertial sensors,” *ACM Comput. Surv.*, vol. 46, no. 3, pp. 1–33, Jan. 2014, doi: 10.1145/2499621.

[23] K. Kawano, S. Kobashi, M. Yagi, K. Kondo, S. Yoshiya, and Y. Hata, “Analyzing 3D Knee Kinematics Using Accelerometers, Gyroscopes and Magnetometers,” in *2007 IEEE International Conference on System of Systems Engineering*, San Antonio, TX, USA, Apr. 2007, pp. 1–6. doi: 10.1109/SYSOSE.2007.4304332.

[24] P. Senthil Selvam, M. Sandhiya, K. Chandrasekaran, D. Hepzibah Rubella, and S. Karthikeyan, “Prosthetics for Lower Limb Amputation,” in *Prosthetics and Orthotics*, M. Arazpour, Ed. IntechOpen, 2021. doi: 10.5772/intechopen.95593.

[25] F. Hamptom and C.P., “Hemipelvectomy Prosthesis”, [Online]. Available: http://www.oandplibrary.org/al/pdf/1964_01_003.pdf

[26] F. H. Sim, “Musculoskeletal Cancer Surgery: Treatment of Sarcomas and Allied Diseases,” *The Journal of Bone and Joint Surgery-American Volume*, vol. 85, no. 8, pp. 1644–1645, Aug. 2003, doi: 10.2106/00004623-200308000-00056.

[27] Y. Zhang, E. Wang, M. Wang, S. Liu, and W. Ge, “Design and Experimental Research of Knee Joint Prosthesis Based on Gait Acquisition Technology,” *Biomimetics*, vol. 6, no. 2, p. 28, May 2021, doi: 10.3390/biomimetics6020028.

[28] G. S. Soh and N. Robson, “Kinematic Synthesis of Minimally Actuated Multi-Loop Planar Linkages With Second Order Motion Constraints for Object Grasping,” in *Volume 3: Nonlinear Estimation and Control; Optimization and Optimal Control; Piezoelectric Actuation and Nanoscale Control;*, Palo Alto, California, USA, Oct. 2013, p. V003T38A004. doi: 10.1115/DSCC2013-4029.

[29] F. M. Kadhim, J. S. Chiad, and A. M. Takhakh, “Design And Manufacturing Knee Joint for Smart Transfemoral Prosthetic,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 454, p. 012078, Dec. 2018, doi: 10.1088/1757-899X/454/1/012078.

[30] Z. W. Lui, M. I. Awad, A. Abouhossein, A. A. Dehghani-Sanij, and N. Messenger, “Virtual prototyping of a semi-active transfemoral prosthetic leg,” *Proc Inst Mech Eng H*, vol. 229, no. 5, pp. 350–361, May 2015, doi: 10.1177/0954411915581653.

[31] H. F. Nweke, Y. W. Teh, M. A. Al-garadi, and U. R. Alo, “Deep learning algorithms for human activity recognition using mobile and wearable sensor networks: State of the art and research challenges,” *Expert Systems with Applications*, vol. 105, pp. 233–261, Sep. 2018, doi: 10.1016/j.eswa.2018.03.056.

[32] Y. Chen, L. Yu, K. Ota, and M. Dong, “Robust Activity Recognition for Aging Society,” *IEEE J. Biomed. Health Inform.*, vol. 22, no. 6, pp. 1754–1764, Nov. 2018, doi: 10.1109/JBHI.2018.2819182.

[33] Y.-J. Hong, I.-J. Kim, S. C. Ahn, and H.-G. Kim, “Activity Recognition Using Wearable Sensors for Elder Care,” in *2008 Second International Conference on Future Generation Communication and Networking*, Hainan, China, Dec. 2008, pp. 302–305. doi: 10.1109/FGCN.2008.165.

[34] H. Zhang and L. E. Parker, “Bio-inspired predictive orientation decomposition of skeleton trajectories for real-time human activity prediction,” in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, Seattle, WA, USA, May 2015, pp. 3053–3060. doi: 10.1109/ICRA.2015.7139618.

[35] F. Martini, R. B. Tallitsch, and J. L. Nath, *Human anatomy*, Ninth edition. NY, NY: Pearson, 2018.

[36] B. Kalita, J. Narayan, and S. K. Dwivedy, "Development of Active Lower Limb Robotic-Based Orthosis and Exoskeleton Devices: A Systematic Review," *Int J of Soc Robotics*, vol. 13, no. 4, pp. 775–793, Jul. 2021, doi: 10.1007/s12369-020-00662-9.

[37] L.-Q. Zhang and G. Wang, "Dynamic and static control of the human knee joint in abduction–adduction," *Journal of Biomechanics*, vol. 34, no. 9, pp. 1107–1115, Sep. 2001, doi: 10.1016/S0021-9290(01)00080-X.

[38] W. Maish, "Anatomical Movements of the Human Body." https://geekymedics.com/anatomical-movements-of-the-human-body/#:~:text=Examples%20of%20internal%20rotation%20include,from%20each%20other%20(Figure%2020)

[39] A. Augustyn, "Tibia," *Britannica*. [Online]. dated: 10 May, 2022, Available: https://www.britannica.com/science/tibia

[40] J. Seladi, "Human Body." Health Line, dated: 10 April, 2022,. [Online]. Available: https://www.healthline.com/human-body-maps/leg#leg-diagram

[41] A. Augustyn, "Fibula," *Fibula Bone*. [Online]. dated: 25 May, 2022, Available: https://www.britannica.com/science/fibula-bone

[42] M. Grimmer, A. A. Elshamanhory, and P. Beckerle, "Human Lower Limb Joint Biomechanics in Daily Life Activities: A Literature Based Requirement Analysis for Anthropomorphic Robot Design," *Front. Robot. AI*, vol. 7, p. 13, Feb. 2020, doi: 10.3389/frobt.2020.00013.

[43] J. Wang, Y. Chen, S. Hao, X. Peng, and L. Hu, "Deep Learning for Sensor-based Activity Recognition: A Survey," *Pattern Recognition Letters*, vol. 119, pp. 3–11, Mar. 2019, doi: 10.1016/j.patrec.2018.02.010.

[44] G. M. Weiss, "WISDM Smartphone and Smartwatch Activity and Biometrics Dataset," p. 5.

[45] M. M. Hamdi, M. I. Awad, M. M. Abdelhameed, and F. A. Tolbah, "Lower limb motion tracking using IMU sensor network," in *2014 Cairo International Biomedical Engineering Conference (CIBEC)*, Giza, Egypt, Dec. 2014, pp. 28–33. doi: 10.1109/CIBEC.2014.7020957.

[46] N. Kern, B. Schiele, and A. Schmidt, "Multi-sensor Activity Context Detection for Wearable Computing," in *Ambient Intelligence*, vol. 2875, E. Aarts, R. W. Collier, E. van Loenen, and B. de Ruyter, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2003, pp. 220–232. doi: 10.1007/978-3-540-39863-9_17.

[47] "PROSTHETIC KNEE OPTIONS." https://www.scheckandsiress.com/patient-information/care-and-use-of-your-device/prosthetic-knee-options/#:~:text=Single%2Daxis%20knees%20are%20basic,walk%20at%20a%20single%20speed.

[48] T. van der Stockt, "Physiopedia," *Prosthetic Knees*. https://www.physio-pedia.com/Prosthetic_Knees

[49] S. S. Saha, S. Rahman, M. J. Rasna, A. K. M. Mahfuzul Islam, and Md. A. Rahman Ahad, "DU-MD: An Open-Source Human Action Dataset for Ubiquitous Wearable

Sensors," in *2018 Joint 7th International Conference on Informatics, Electronics & Vision (ICIEV) and 2018 2nd International Conference on Imaging, Vision & Pattern Recognition (icIVPR)*, Kitakyushu, Japan, Jun. 2018, pp. 567–572. doi: 10.1109/ICIEV.2018.8641051.

[50] A. Alamdari and V. N. Krovi, "A Review of Computational Musculoskeletal Analysis of Human Lower Extremities," in *Human Modelling for Bio-Inspired Robotics*, Elsevier, 2017, pp. 37–73. doi: 10.1016/B978-0-12-803137-7.00003-3.