



**REGIONAL CENTRE OF EXCELLENCE IN BIOMEDICAL ENGINEERING AND E-HEALTH (CEBE)**

**Design and Prototyping of a Gait Monitoring System for Lower Limb  
Prosthesis Users**

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A Dissertation Submitted to the Regional Centre of Excellence in Biomedical Engineering and e-Health (CEBE), University of Rwanda as partial fulfilment of the requirements for the Master's Degree in Biomedical Engineering.

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**DECLARATION**

I, TUYISENGE Liberee, declare that this dissertation entitled “Design and Prototyping of a Gait Monitoring System for Lower Limb Prosthesis Users” is my original work based on research and prototype and has not been submitted for any other degree or professional qualification.

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**CERTIFICATE**

This is to certify that the project entitled “Design and Prototyping of a Gait Monitoring System for Lower Limb Prosthesis Users” is a record of original work done by 222000242, a MSc. Degree student in Biomedical Engineering.

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## **ABSTRACT**

Physical impairments, such as missing limbs as a result of illness, genetic disorders, or amputation, have a profoundly harmful impact on an individual's quality of life, welfare, and economic prospects in many nations. Functional prosthetics that are suitable for their intended use and are inexpensive, powerful, and reliable are required. They must be simple to make, maintain, and/or repair and suited for long-term usage. Gait analysis, which examines human locomotion holistically, is crucial in identifying patterns in such activity. Lower limb prosthesis users' physical and mental health are strongly impacted by their gait quality. Amputees of the lower extremities have mobility issues, which will lower their quality of life. To build an interactive control of the amputee prosthesis environment system, wearable sensors are widely utilized to analyze spatiotemporal, kinematic, and kinetic characteristics. Controlling lower limb prosthetic devices requires knowledge of gait events and the gait phase detection of an amputee's mobility. In order to restore mobility after amputation, the patient is fitted with a prosthetic device. However, a number of factors including the individual's health, the type of amputation, prosthetic device performance, and the fit of the prosthetic socket, affect how much the person recovers. One of the objectives of the World Health Organization's 2030 Agenda for Sustainable Development is that people will be able to get assistive products and services to enhance their quality of life, as well as inexpensive, high-quality health treatments. In this thesis, a web-based system that will help clinicians track gait problems and prosthesis deviation by providing real-time data during rehabilitation. The proposed system uses MPU9250 sensor that combines accelerometer, magnetometer and gyroscope to detect spatial temporal gait parameters such as step length, stance phase duration, and ankle flexion angle and send obtained information of the possibility of the specified improper gaits or prosthetic fit via wireless communication system to the web application and later sent to cloud database for future use. The data received from the sensor was analyzed by the Nodemcu micro-controller and sent to the web dashboard to be accessed by clinicians via WIFI. The gait parameter values were recorded, analyzed and used to indicate if the walk cycle of a person is normal or it has any abnormality. This device is a practical option for objective gait and prosthetic deviations tracking in clinical rehabilitation because it is simple and easy to put on and take off. The gait monitoring system was able to detect gait and prosthetic deviations and future study will investigate its use in home environment.

**Keywords:** Amputees; Lower limb; Disabilities; Prosthesis Devices; Sensor; Quality of life; ...

## LIST OF ACRONYMS

<b>AD:</b>	Alzheimer's disease
<b>AOT:</b>	Action-Observation Therapy
<b>EMG:</b>	Electromyogram
<b>FSR:</b>	Force Sensing Resistor
<b>GORH:</b>	Gatagara Orthopedics and Rehabilitation Hospital
<b>HVP:</b>	Home de la Vierge des Pauvres
<b>IMUs:</b>	Inertial Measurement Units
<b>LLA:</b>	Lower Limb Amputee
<b>MS:</b>	Multiple Sclerosis
<b>PAI:</b>	Physical Activity Improvement
<b>PD:</b>	Parkinson's disease
<b>Subject/ Patient:</b>	Person subjected or to be subjected to clinical gait assessment
<b>WHO:</b>	World Health Organization

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## CHAPTER 1. GENERAL INTRODUCTION

### 1.1. Introduction

One of the most basic forms of human mobility, walking is essential for both physical and mental health. The way we walk, or our gait, is dependent on complex interactions between key components of our neurological, musculoskeletal, and cardiorespiratory systems[1]. These systems must function effectively for safe walking, and failure in any one of them could potentially cause abnormalities in the gait pattern. Thus, gait monitoring is a crucial area for research in many areas of medicine, from Parkinson's neurorehabilitation to treating the lower limb amputee (LLA) population [2]. Rwanda has 11,537,934 persons aged 5 years and above out of whom 391,775 (174,949 males and 216,826 females) have disability. This implies that at the national level, 3.4 % of the resident population aged 5 years and above have a disability with mobility limitation at 122,999 (1.1 %) Out of all Persons with disabilities according to the National Census of 2022[3].

#### 1.1.1. What is Gait?

Gait is the action of walking (locomotion). It is a complex, movement that is the coordinated action of many joints and muscles of our musculoskeletal system. It mostly includes the movements of the lower limbs, upper limbs, pelvis, and spine[4]. Studies regarding gait have progressed the understanding of walking from the physiological aspects of bones, ligaments, and the activation of muscles, and others to more specific techniques and patterns which have led to the discoveries of new rehabilitation methods and the categorization of various walking impairments[5]. Before gait can be analyzed the basic concepts namely the gait cycle and basic parameters must be introduced.

#### 1.1.2. Gait cycle

A complete gait cycle is defined as the movement from one foot strike to the successive foot strike on the same side. The **stance phase**, which begins with **foot strike** and ends with **toe-off**, usually lasts for about 62% of the cycle; the **swing phase**, which begins with **toe-off** and ends with **foot strike**, lasts for the final 38%. During each cycle, a regular sequence of events occurs. Expressing each event as a percentage of the whole normalizes the gait cycle. Initial foot strike, or **initial contact**, is designated as 0%; the successive **foot strike** of the same limb is designated as 100%. The events of the gait cycle, which define the functional periods and phases of the cycle, are **foot strike**, **opposite toe-off**, **reversal of fore shear to aft shear**, **opposite foot strike**, **toe-off**, **foot clearance**, **tibia vertical**, and **successive foot strike**. The stance phase is divided into three major periods: **initial double-limb support**, or loading response; **single-limb stance**; and **second double-limb support**, or pre-swing. The defining events for initial double-

limb support are foot strike and opposite toe-off. The defining events for single-limb stance are opposite toe-off and opposite foot strike. Single-limb stance is further divided by the event of reversal of fore to aft shear into midstance and terminal stance. Terminal stance refers to terminal single-limb stance and should not be confused with second double-limb support. The swing phase is divided into **initial swing**, **mid-swing**, and **terminal swing**. The defining sequential events for initial swing are toe-off and foot clearance. Mid-swing begins with foot clearance and ends with tibia vertical. Terminal swing begins with tibia vertical and ends with foot strike as indicated in phases of gait cycle[6].

### **1.1.3. Basic measurements**

The fundamental purpose of gait analysis is to determine the overall locomotor function of a subject. This is accomplished by comparing and contrasting different gait parameters against expected values. Modern advancements in technology have allowed clinicians to record a variety of different parameters using the many tools at their disposal. However, the gait function can still be evaluated using only the most elementary parameters, namely the spatial and temporal parameters.

#### **1.1.1.1. Spatial parameters**

##### **Step/Stride**

Length/Step length is the distance one part of a foot travels away from the opposite foot. Typically, the step length is measured from either the heel contact or toe-off point of a step cycle. Furthermore, stride length can be described as the distance between the successive points of the same foot. For conventional gait cycles the stride length or step lengths for both feet are approximately equal (75-80 cm), this is referred to as a symmetric gait pattern. As a result, clinicians will often observe for any asymmetric gait patterns, as represented in asymmetric gait patterns during walking [7].

##### **Step Width**

Step width is the separation distance between both feet in the Medio lateral direction and is most commonly measured from the center point of the heel. Normal step widths range between 8-10 cm and are seen to affect walking stability if varied greatly.

#### **1.1.1.2 Temporal parameters**

##### **Cadence/Step Rate & Step/Stride Time**

Cadence is the total number of steps taken in one minute, also known as the step rate. This is closely related to the step/stride time, which can be described as the duration to complete one step/stride cycle respectively.

### **1.1.1.3. Spatiotemporal Parameter**

#### **Walking Speed**

Combining both spatial and temporal measurements yields walking speed. Walking speed is directly related to the step rate and step length:

$$\text{Walking speed (m/s)} = \frac{\text{Step rate} \times \text{step length}}{60}$$

## **1.2 Background and motivation**

### **1.2.1 Background**

Limb loss is a devastating experience that can have a profound impact on a person's life. Whether it's due to injury, illness, or congenital conditions, losing a limb can be a traumatic event that requires significant physical and emotional adjustment[8]. It limits functioning and restricts participation in various environments. Persons with lower limb amputations (PLLA) experience challenges ranging from self-care and independence to psychological disorders that negatively impact their functioning[9] unfortunately, the exact number of people who have had amputations worldwide is difficult to ascertain, as many countries do not keep records of the number of people with limb amputation[10]. Amputees should have a fully functional and physical assessment and rehabilitation should be based around personalized functional goals. Individualized exercise programs are developed after a thorough assessment. Awareness of normal gait and the deviations and their cause formulates the basis of the correct rehabilitation of the individual [11][12]. There are numerous techniques that can be used during rehabilitation and not all of them will be appropriate for each individual, therefore the program and technique must be applied to each individual and reviewed regularly to ensure it remains adequate[13][11]. Every year, more people all over the world have their lower limbs amputated due to vascular disease, injuries, and the effects of diseases like diabetes, cancer, and vascular disease. High-income countries have reported a decreasing incidence of lower limb amputees, but the situation in many low and middle income countries is unknown[14]. The burden of injuries and amputation in low- and middle-income countries is substantial, although much of the impact is potentially avoidable. However, whilst we know the burden is high, we don't know how high. We cannot confidently quantify how limb loss affect

victims, their families and wider society in the developing world because no-one collects this data[15].

### **1.2.2 Motivation**

There are several important reasons to design a gait monitoring system for older adult lower limb prosthesis users in Rwanda. With the use of objective data, this method may facilitate early detection and treatment of gait problems, improve prosthetic fitting, and encourage preventative care practices. This can eventually lower healthcare costs and time and provide clinicians with objective data for customized interventions. This innovative method contributes to a more inclusive and supportive healthcare system by addressing the specific healthcare needs of this population in Rwanda and by encouraging mobility, independence, and general well-being among older adult prosthesis users.

### **1.3 Problem statement**

An individual usually gets a lower limb amputation in response to severe trauma or to treat problems from vascular disorders. The patient is fitted for a prosthetic limb after the amputation, and then receives rehabilitation. Unfortunately, many of these people only regain a limited amount of mobility after years of pain and difficulties from using prosthetic limbs, despite advancements in health and technology. Among all major limb amputations, transtibial amputation also referred to as "below knee" amputation is one of the most commonly carried out procedures[16]. Amputation is a horrific experience that profoundly affects the victim's life. The artificial limb must work as closely as possible to the natural limb in order to restore a healthy, active lifestyle and support limb health. Unfortunately, poor prosthetic fit leads to persistent back pain in transtibial amputees. Inadequate prosthetic fit can cause skin issues, including irritating contact dermatitis and pressure sores on residual limbs, in addition to musculoskeletal injuries [17]. The ability of the person to resume normal gait is significantly influenced not only by the prosthetic limb's performance but also by the socket's fit and comfort. Inadequate or misfitting socket fittings can cause severe pain and friction and ulcers in the person's remaining limb. Over time, these consequences may cause additional issues, particularly in people with diabetes or vascular illnesses. These people's decreased mobility may contribute to obesity and other health issues that lower their quality of life. Rwanda lacks a system to monitor prosthetic fit and gait deviations, causing skin damage, pain, gait abnormalities, reduced mobility, and prosthetic damage to lower limb amputees who are using prostheses. So, the proposed gait monitoring system can improve fit, gait, and prevent gait problems.

## **1.4 Research Questions (Hypotheses)**

The following questions are the baselines which guided this study:

1. What are the specific challenges faced by clinicians and older adult prosthesis users at HVP Gatagara and Inkurunziza Orthopedic Hospital with currently available gait monitoring system?
2. How can the identified challenges with current gait monitoring system inform the design and development of a more effective system architecture tailored to the needs of lower limb prosthesis users in Rwandan healthcare settings?
3. What are the key features and functionalities that clinicians require in a web application prototype for gait monitoring, and how can these be integrated to facilitate early detection and tracking of gait problems in lower limb prosthesis users?
4. How accurately does the designed gait monitoring system measure important gait parameters? How can the system be further improved to increase the reliability and accuracy of its early gait problem identification in older persons who wear prosthetics?

## **1.5 General Objective**

This project aims to design and prototyping a Gait monitoring system for older adult lower limb prosthesis users that will help clinicians identify and treat gait problems early on in Rwanda.

### **1.5.1 Specific Objectives**

To achieve the general objective of this project, the following are specific objectives:

1. To investigate challenges with existing gait monitoring technologies for lower limb prosthesis users at HVP Gatagara, and Inkurunziza Orthopedic Hospital;
2. To design a system architecture for enhanced gait monitoring system for lower limb prosthesis users;
3. To develop a web application prototype of a gait monitoring system that helps clinicians track gait problems early on;
4. To test the performance of the system to ensure its accuracy.

## **1.6 Study Scope**

This study focused on collecting and analyzing spatiotemporal gait parameters in order to study the gait of people with amputation of their lower extremities in Rwanda. Three different gait parameters, step length, stance phase duration and ankle flexion, that are commonly observed

during normal work activities were considered. The collected data were studied to determine the dependence of these parameters on the selected gait of the individuals considered. Furthermore, changes observed over time in the collected data were studied to identify any changes in limb health.

### **1.7 Significance of the study**

The study of designing a gait monitoring system for lower limb prosthesis users in Rwanda is meant to identify and treat gait problems early on which can help preventing further complications and assist in tracking users 'progress in rehabilitation programs. The system will assist users in addressing problems that might cause discomfort or pain by offering real-time feedback and insights about gait anomalies, thereby enhancing their physical well-being. Through more active participation in everyday activities and greater independence, users of lower limb prostheses can greatly improve their quality of life. Additionally, the designed system can help with rehabilitation efforts by enabling medical professionals to track results and promptly modify the prosthesis or rehabilitation strategy, thus shortening the recovery period.

### **1.8 Organization**

Chapter 1 gives the introduction of this thesis, the problem statement, the research questions, the objectives, and the study scope, the significance of the study, the thesis organization and the summary. Chapter 2 discusses the literature review on available gait monitoring systems in clinics. It also discusses about wearable sensor, research gap and research design. In Chapter 3, the used methodology is explained for achieving the specific objectives, explains the data collection from questionnaire about gait monitoring systems, the proposed system, the hardware and software used to build the system. In Chapter 4, the result and the analysis of the project are presented together with discussion, and finally in Chapter 5, the overall conclusion of the project is drawn and future recommendations that can be done to improve this project are presented.

### **1.9 Summary**

This chapter introduces the work to be presented in this thesis. The objectives of the work are presented together with its scope. One can notice that the developed gait monitoring system in Rwanda use cloud database receiving data about prosthesis deviations from Node MCU using ESP8266 WIFI module. The data present on the cloud can be accessed by end users (Clinicians) using the developed web application system accessed from their smartphones or computers. Hope the reader will enjoy the extensive work presented afterwards.

## **CHAPTER 2. LITERATURE REVIEW**

### **2.1 Introduction**

This Chapter reviews studies and developments in the field of gait monitoring systems applied for lower limb prosthesis users. The Chapter suggests some advantages and limitations of all the existing systems, and the relevant questions and recommendations about gait monitoring systems for future developments are presented in the following Chapters.

### **2.2 Gait outcome measurements**

Healthcare professionals have created a variety of gait outcome measures over the last few decades to assess the physical and mental challenges faced by LLAs [18]. They can be divided into subjective and objective evaluations. While objective measurements are obtained through quantitative monitoring of patient outcomes, from simple two-minute walk tests to more in-depth analyses made possible by force platforms, subjective assessments are based on personal perceptions reported by patients or clinicians[19][20]. In Rwanda, the number of persons with physical disabilities, including those with lower limb amputation (LLA) is estimated at 5% of the general population, of which 1.6% had LLA according to the National Census of 2012 (National Institute of Statistics of Rwanda 2014)[21]

Personal bias and poor accuracy are crucial factors in doctors' assessments of gait quality, even though qualitative and subjective health outcomes are essential components of clinical diagnosis and treatment[20]. Furthermore, it might be challenging to assess many health outcomes from a third-person perspective, including psychometric (like body image) and functional outcomes (like phantom pain). Patient-reported outcome metrics are thus employed to support clinical decision-making [22]. For instance, patient judgments of the placement and intensity of pressure points are frequently used to evaluate prosthetic fit [23]. Based on their assessments, patients fill out questionnaires about their health issues. Although this data can support clinical evaluations, they are mostly subjective and prone to changes in the patient's emotions and feelings.

Objective outcome indicators have significantly increased in importance in credible and reliable treatment procedures as a result of the shift toward evidence-based practice in the health sciences[24]. Performance-based and instrument-based assessments are the two main categories of objective measurements[25]. For gait rehabilitation, the former kind of objective evaluations can be as straightforward as using a ruler to check the prosthesis socket's movement or a stopwatch to time a two-minute walk test; however, the latter kind of objective evaluations can be quite sophisticated and include things like using gait mats[19] or wearable in-socket

monitoring systems [26]. Instrument-based measures assess the biomechanical, physiological, and spatiotemporal outcomes as the three key outcome parameters[27][28].

### 2.3 Quantitative gait analysis

Although some outcome measures require qualitative inputs, it is essential to quantify outcomes utilizing sensing technologies to get results that are standardized and have high dependability. Gait is made up of a series of walking's repetitive movements. One gait cycle is the period between when one foot first makes contact with the ground and when that same foot makes contact with the ground again. The stance and swing phases make up a gait cycle. A gait cycle is represented by the key events in phases of gait cycle [29].

The systematic study of human locomotion is known as quantitative gait analysis [25][30], and it entails the measurement, description, and evaluation of variables that define the walking gait. From a simple step-per-minute count to in-depth kinematic assessments of body parts, gait analyses include a wide range of topics[31]. Human locomotion's kinetic, kinematic, and spatiotemporal properties are evaluated via gait analysis techniques [30]. Each category of gait analysis (Table 2.1) requires a different set of wearable sensors.

Table 2. 1: Biomechanical parameters of gait

Kinetic	<ul style="list-style-type: none"> <li>➤ Force- and pressure-related parameters: Ground reaction force (GRF), in-socket pressure, etc.</li> </ul>
Kinematic	<ul style="list-style-type: none"> <li>➤ Position and orientation of body segments: Joint angle, joint angular velocity, and joint angular acceleration</li> </ul>
Spatiotemporal	<ul style="list-style-type: none"> <li>➤ Distance-related parameters: Step length, stride length, velocity, etc.</li> <li>➤ Time-related parameters: Stride time, swing time, etc.</li> </ul>

Motion capture devices and force plates have become the industry standard for measuring gait parameters in recent years [32][33] and they usually have arrays of piezoelectric components, strain gauges, force-sensing resistors, or beam load cells as represented in Arrays of force-sensing resistors [32] and Conventional gait analysis using GAITRite walkway [16]. They are used to quantify kinetic parameters, which are variables related to ground reaction forces and moments in human walking.[34]. On the other hand, motion capture systems gather gait kinematic parameters using a combination of optical, mechanical, and/or electrical sensors [34]. These tools have grown to be vital for clinical diagnosis and care [35]. Although these systems are perfect for a thorough investigation of human locomotion, they are expensive, need a

specialist to run them, and take a lot of time to set up and interpret the data, making them unfeasible for use in a clinical environment. Wearable technology has therefore become more valuable in gait analysis.

## **2.4 Wearables for gait analysis**

Any smart electronic device that can be attached to clothing or worn on the body and offers practical patient-centric medical information is referred to in the healthcare industry as wearable technology [36][37]. In addition to having the potential to significantly improve quantitative health evaluations, wearables have emerged as portable, affordable alternatives to conventional health monitoring technologies. They have been used for a variety of purposes, from encouraging physical activity to more complicated uses in surgery [38][39][40].

Remote gait analysis and activity monitoring have significantly improved over the past ten years due to the quick development of portable electronics[41][42]. Wearable technology has advanced over the past ten years to become even more portable, useful, and affordable. In just eight years, wearable gait monitoring technologies have become more portable as represented in the improvement in the portability of wearable systems from 2010 to 2018 for Xsens sensing system and eShoes [43][44]. The interference in ambulation has been decreased due to these changes. As a result, even after being released from rehabilitation facilities, patients can still benefit from such systems at home, and clinicians can keep an eye on their development.

### **2.4.1 Existing technologies**

Several sensors, including electromyogram (EMG) sensors, inertial measurement units (IMUs), and force sensing resistors (FSRs), have been evaluated and used in the field of gait analysis to quantify various biomechanical and physiological outcomes related to ambulation quality [45][46]-[47]. The activity monitors ActiGraph (LLC, Pensacola, USA) and activPAL (PAL Technologies, Glasgow, UK) are two of the most widely used health monitoring devices. These devices monitor neighborhood activity using a variety of sensors, including global positioning systems [48], EMG [49], and accelerometers[50]–[51]. Activity monitors use gait measurements including cadence, steps per day, minutes active per day, and the peak activity index to measure how well a person can move around[52]. They were able to overcome difficulties in activity level monitoring that were previously inaccurate in self-reported assessments [53]. Activity monitors can assist in monitoring a patient's activities during therapy, but they are unable to identify complex gait patterns or track improvements in walking form. Positions and orientations of different body segments, as well as the distribution of pressure in the insole during a gait cycle, are necessary for the complex monitoring of the kinematic, kinetic, and time-distance

characteristics of the gait. Wearable systems have evolved over the last few years into more thorough monitoring tools that can gather spatiotemporal and specific kinetic gait characteristics. Recent investigations have shown that innovative systems and gold-standard gait walkways as represented in Mobile Gait Analysis using wireless systems for Smart Insole[49] and IMU [50] show high agreement in stride duration, stance time, swing time, double support time, step time, and cadence [54][43][44]. eShoes as represented in a wearable for gait analysis[40] is one of the most innovative and portable systems now available. It is made up of six-DOF IMU (three-DOF accelerometer and three-DOF gyroscope) and insole pressure sensors. In comparison to the industry standard, eShoes have been validated and proven to be capable of measuring both spatial and temporal gait parameters [54]. It has been shown that other IMU-based systems have a good correlation with traditional gait analysis for several gait measurements [55].

#### **2.4.2. Gap in research**

Two challenges stand in the way of routine clinical assessment using wearable technologies, as was already indicated before. From a technology standpoint, many wearable medical devices are made to meet the demands of young, healthy individuals and are not appropriate for use by several other patient populations. Only a few wearable-based gait analysis studies have taken gait problems in the amputee population into account [56]. So, more research is necessary to determine if wearable-based gait monitoring is accurate and reliable for the amputee community [41]. Additionally, population-specific designs have been proposed [56] for a variety of wearable system components, including size, positioning, and physical characteristics as well as hardware components and gait model estimation. Clinically, despite wearables' accessibility and potential advantages in differentiating patients' capacity and performance, adoption and acceptance by medical professionals continue to be key difficulties [51]. The results of a thorough study showed that, despite their interest in IMUs, clinicians had very high expectations for data visualization before they thought about employing them. After all, many pieces of recently produced technology have interfaces that necessitate technical knowledge to operate and analyze the output [45][54]. Additionally, patient motivation is still a problem because many wearable technologies in development require support for setup [57] and/or have complicated user interfaces as shown in the Prototype of Wearable Gait Monitoring System's figure [58].

Only a few articles, as of 2020, have provided additional techniques for accurately monitoring lower limb prosthetic use in addition to a basic step count [59][60][57][61]. As a result, we continually need to undertake research and create systems in response to the challenges the clinical population in question experiences. To design and develop gait detection systems and

display interfaces that are fully functional and useful, clinician advice and patient preferences should be taken into account. It is hoped that researchers will be able to illustrate the true usefulness of wearables and encourage older people and prosthesis users to use them by coming up with more practical and cheap solutions.

## **2.5 Summary**

This literature review covers the state-of-the-art on conventional gait analysis approaches, wearables for gait analysis including existing technologies and gap in research. Therefore, in this research, considering all the various aspects described above, an inexpensive, wireless, portable, and simple and easily to use, gait monitoring system should be designed and developed for users and clinicians in clinics. Also, the detail research gap is described where many wearable medical devices are made to meet the demands of young, healthy individuals and are not appropriate for use by several other patient populations and only a few wearable-based gait analysis studies have taken gait problems in the amputee population into account. To overcome these limitations, an affordable wearable gait monitoring system was developed.

## **CHAPTER 3. RESEARCH METHODOLOGY**

The current chapter concerns the methodology used to achieve the objectives of the gait monitoring system for lower limb prosthesis users in Rwanda.

### **3.1 Research Process**

The research process for developing a gait monitoring system for lower limb prosthesis users follows a systematic approach, drawing upon insights from various studies in the field. Firstly, a comprehensive review of existing literature is conducted, focusing specifically on gait monitoring systems tailored for individuals with lower limb prosthesis [56]. This entails analyzing academic journals and relevant research publications to ascertain the current state-of-the-art technologies and methodologies in this domain. Key studies such as Development of a Wearable Gait Monitoring System for Lower Limb Prosthesis [50] and Design and Validation of a Mobile Gait Analysis System for Lower Limb Prosthesis Users [62] serve as foundational references, providing insights into the challenges, advancements, and methodologies employed in the development of gait monitoring systems. Additionally, research articles like Integration of Ground Reaction Force Measurement System with Prosthetic [61] contribute valuable knowledge regarding the incorporation of ground reaction force measurement technologies into prosthetic devices. These insights help in understanding the biomechanical aspects involved in gait analysis and prosthetic limb function. Furthermore, studies such as Portable Motion Analysis System for Monitoring Gait in Transtibial Amputees [63] and Development of a Portable Gait Analysis System for Lower Limb Prosthesis Users [54] offer practical approaches and methodologies for implementing portable gait analysis systems. These papers provide guidance on the design, validation, and application of such systems in real-world settings, facilitating the development of effective monitoring solutions for prosthetic users.

By synthesizing findings from these referenced studies and others, the research process aims to inform the design, development, and validation of a comprehensive gait monitoring system tailored to the specific needs of individuals with lower limb prosthetics. Through iterative testing, refinement, and validation, the goal is to create a system that enhances prosthetic fit, alignment, training, and ultimately improves the reintegration of users into pre-injury activities.

### 3.1.1 Study design

The study design is defined as the drawing for fulfilling research objectives and answering hypotheses[64]. In addition, it refers to the strategy that a researcher adopts to integrate the various elements of the study in a comprehensive and logical manner to ensure that the research problem is exhaustively addressed. Gait monitoring wearable systems have advanced significantly over the past two years, as mentioned in the previous section, but more work needs to be done before they can be adopted commercially as equipment for rehabilitation. The main objective in this case was to develop a practical gait monitoring system that clinicians and prosthesis users could utilize as a tool for rehabilitation. The most important aspects of its design are practicality, adaptability, ease of use, and low energy usage.

### 3.1.2 The data analysis from research questionnaires

A sample of 30 patients who use prosthesis every day was selected and asked questions about gait and prosthesis use. The analysis of data from questionnaire was done using excel. The data collected from questionnaire are used for designing gait monitoring system, solution to lower limb prosthesis users.

The questions and analyses are in the following diagrams.

Q1. What are the main challenges you face while using your prosthesis on a daily basis?

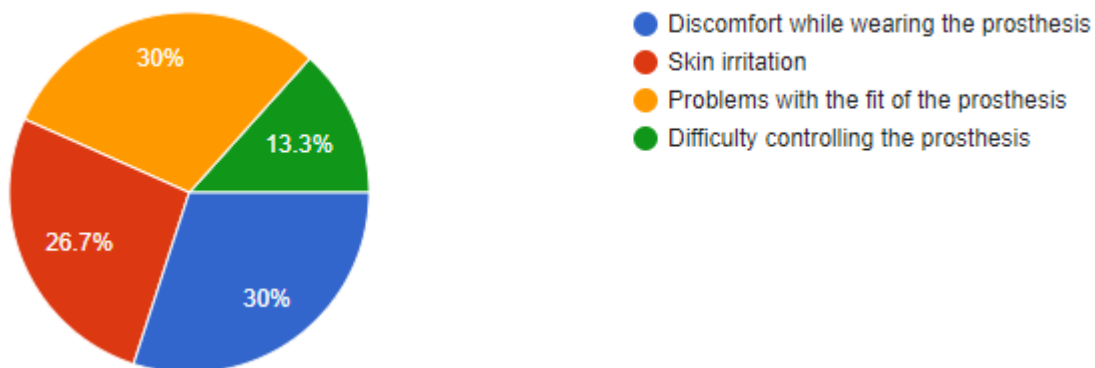


Figure 3. 1: What are the main challenges you face while using your prosthesis on a daily basis?

The Figure 3.1 shows that 30.00% of responders gave responses of having problems with the fit of the prosthesis, 30.00% of responders gave responses of being discomfort while wearing the prosthesis time, 26.7% gave the responses of having skin irritation and 13.3% gave responses of having difficulty of controlling the prosthesis.

Q2. How long have you been using a lower limb prosthesis?

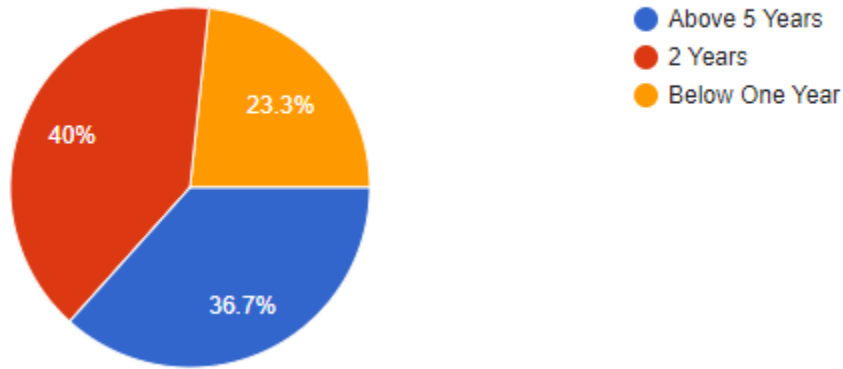


Figure 3. 2: How long have you been using a lower limb prosthesis?

The Figure 3.2 shows that 40% of responders gave responses of period of having prosthesis is 2 years ago, 36.7% of responders gave the responses of having prosthesis is above 5 years and 23.3% gave the responses of having prosthesis is below one year.

Q3. Are you satisfied with the current functionality of your prosthesis? (Yes/No)

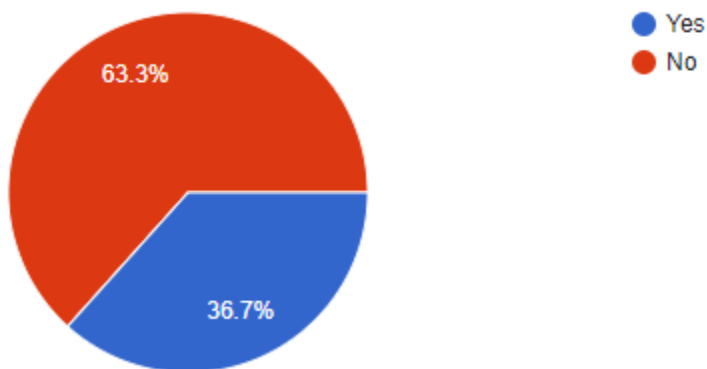


Figure 3. 3: Are you satisfied with the current functionality of your prosthesis? (Yes/No)

The Figure 3.3 shows that 63.33% of Responders gave the responses YES. This means that they are satisfied with the functionality of their prostheses and 36.67% of Responders gave the responses NO. This means that they are not satisfied with the functionality of their prostheses

Q4. Do you know anything about monitoring system? Answer YES or NO

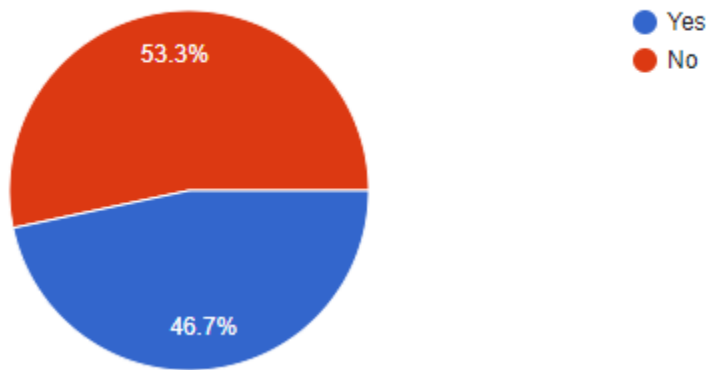


Figure 3. 4: Do you know anything about monitoring system? Answer YES or NO

The Figure 3.4 shows that 53.3% of Responders gave the responses YES. This means that they have some information about monitoring system and 47.7% of Responders gave the responses NO. This means that they have any information about monitoring system.

Q5. Is it the first time do you understand monitoring system? Answer Yes or NO

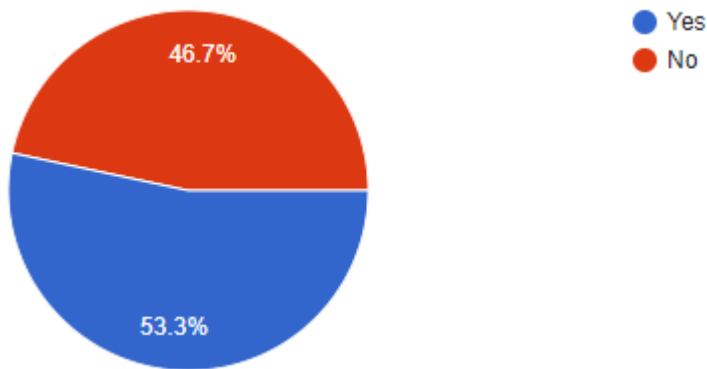


Figure 3. 5: Is it the first time do you understand monitoring system? Answer Yes or NO

The Figure 3.5 shows that 48.3% of Responders gave the responses YES. This means that it is their first time to hear about monitoring system and 51.7% of Responders gave the responses NO. This means that they already heard about monitoring system.

Q6. Have you ever used any gait monitoring system with your prosthesis before? (Yes/No)

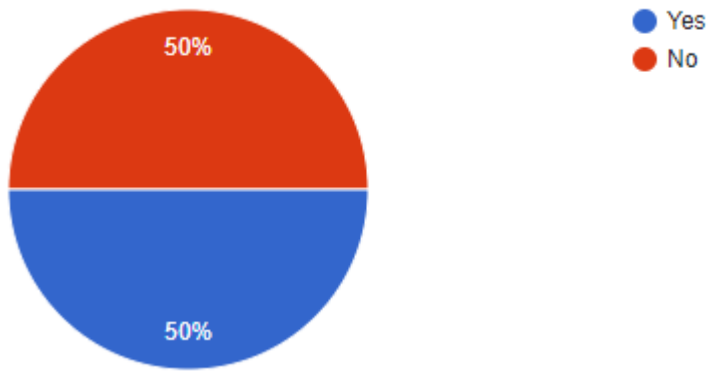


Figure 3. 6: Have you ever used any gait monitoring system with your prosthesis before?  
(Yes/No)

The Figure 3.6 shows that 50% of Responders gave the response YES. This means that they have used a gait monitoring system and other 50% of Responders gave the response NO which means that they didn't use a gait monitoring system.

Q7. Are you satisfied to use this existing method of monitoring prosthesis deviations in prosthesis users? Answer YES or NO

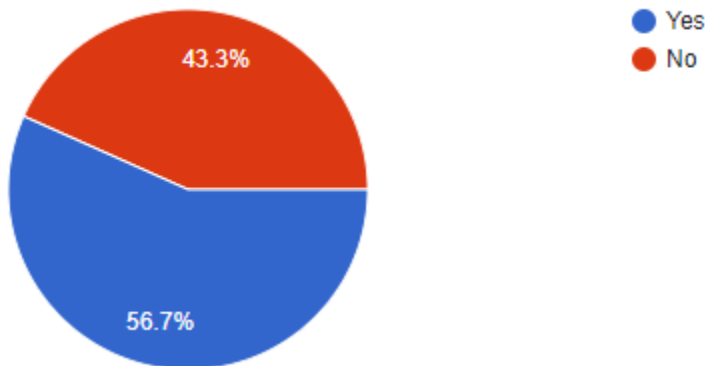


Figure 3. 7: Are you satisfied to use this existing method of monitoring prosthesis deviations in prosthesis users? Answer YES or NO

The Figure 3.7 shows that 43.3% of Responders gave the responses YES. This means that they are satisfied with the existing method of monitoring gait and prosthesis deviations in lower limb prosthesis users and 56.7% of Responders gave the responses NO. This means that they are not satisfied with the existing method of monitoring gait and prosthesis deviations in lower limb prosthesis users.

Q8. Is there any advantage of using existing system of monitoring lower limb prosthesis users?  
Answer Yes or No

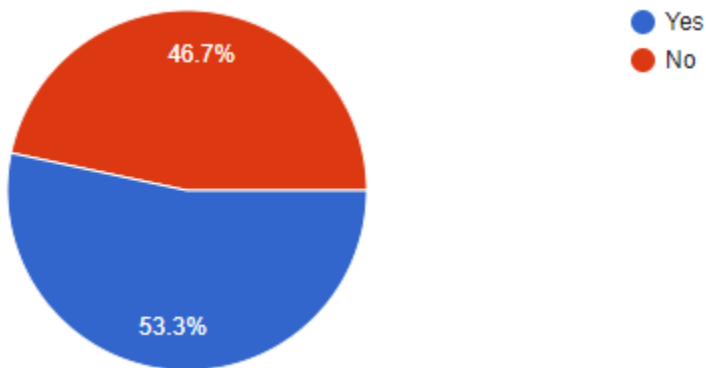


Figure 3. 8: Is there any advantage of using existing system of monitoring lower limb prosthesis users? Answer Yes or No

The Figure 3.8 shows that 46.7 % of Responders gave the responses YES. This means that there is an advantage in using existing system of monitoring lower limb prosthesis users and 53.3% of Responders gave the responses NO. This means that there is no advantage in using existing system of monitoring lower limb prosthesis users.

Q9. Would you prefer a device that is integrated with your existing prosthesis or a standalone device?

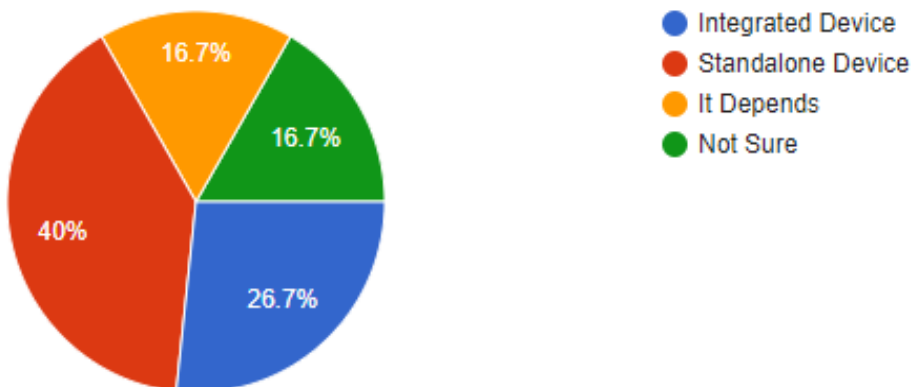


Figure 3. 9: Would you prefer a device that is integrated with your existing prosthesis or a standalone device?

The Figure 3.9 shows that 40.00% of responders gave responses that they prefer standalone device 26.7% of responders gave responses that they prefer integrated device, 16.7% gave the responses of having skin irritation and 16.7% gave responses of having difficulty of controlling the prosthesis.

According to the data coming from the survey done, we developed the system gait monitoring system in Rwanda that will solve all problems seen in the diagrams above that prosthesis users in Rwanda are facing especially those at HVP Gatagara, and Inkurunziza Orthopedic Hospital.

### **3.2 Research Design Method**

The wearable prototype consists of MPU-9250 made of Accelerometer, magnetometer and gyroscope sensors, microcontroller, GSM, a web application, and a cloud database (Figure 3.2). MPU-9250 is attached to a NodeMCU device with an ESP8266 WIFI module. Together, they constitute the peripheral side of the wearable system. A web application receives data from the NodeMCU device through an ESP8266 WIFI connection and sends the stored data to a cloud database.

#### **3.2.1 Proposed system diagram**

The block diagram (Figure 3.10) below of this project shows how each part contribute to make the working system. The system is supplied with a rechargeable lithium battery of 5V so that it can start working and in the heart of this circuit we have Nodemcu ESP 8266 for data processing, decision making and coordination based on the program stored in this component. It receives the data from the sensor and make a decision if it can send the alert to the user or not. It has ESP8266 for wireless communication which help NodeMCU to send the data to the cloud database. As clinicians have to be notified in case of critical condition, we used GSM which will receive a command from NodeMCU and then send SMS and call to the clinicians.

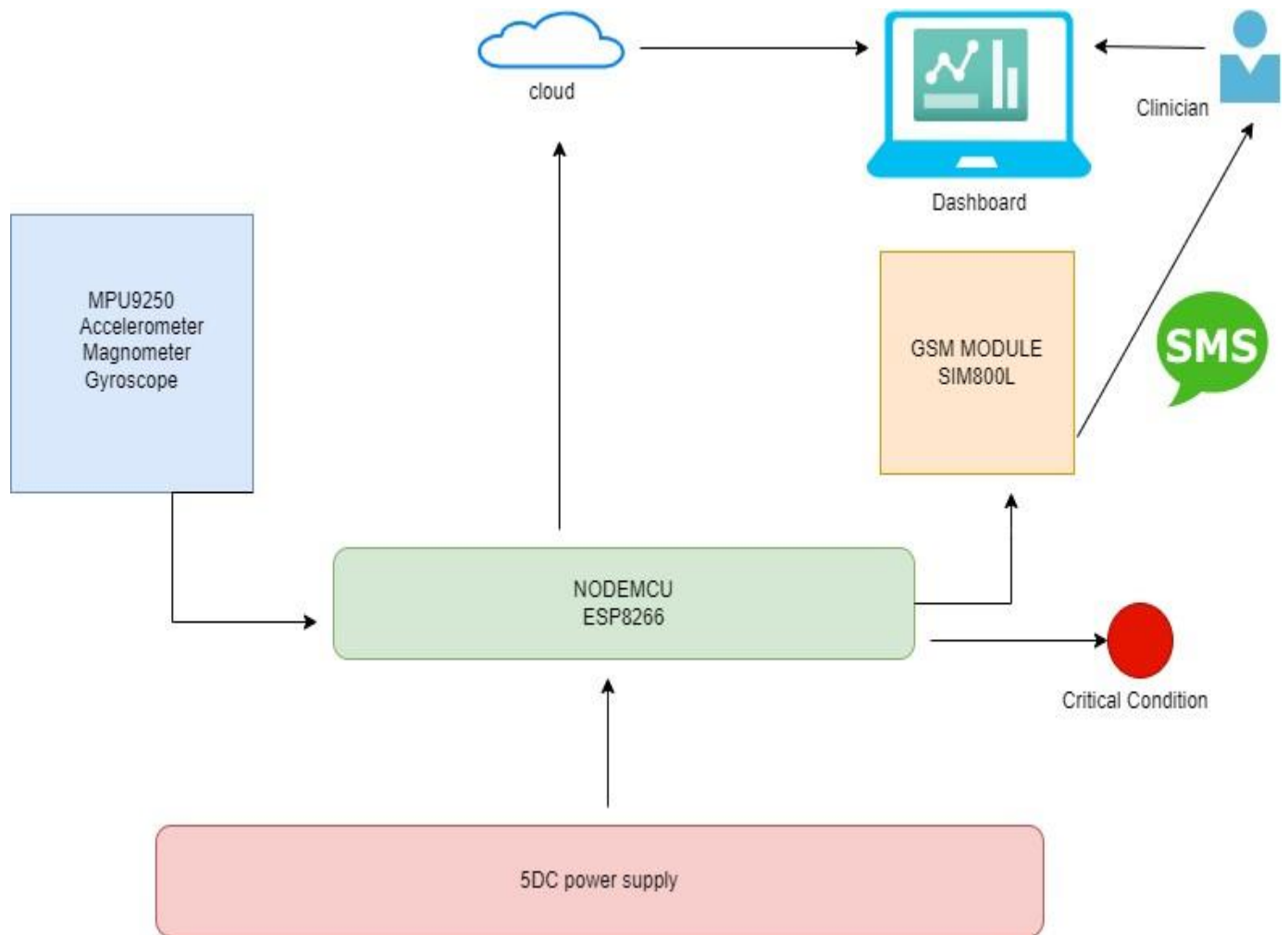


Figure 3. 10: Proposed wearable system architecture

### 3.2.2 System Design Flowchart

We create a system design flowchart (Figure 3.11) to illustrate the sequential steps involved in developing our gait monitoring system. This includes sensor selection, firmware development, server setup, web dashboard design, and testing, all within a specified timeframe.

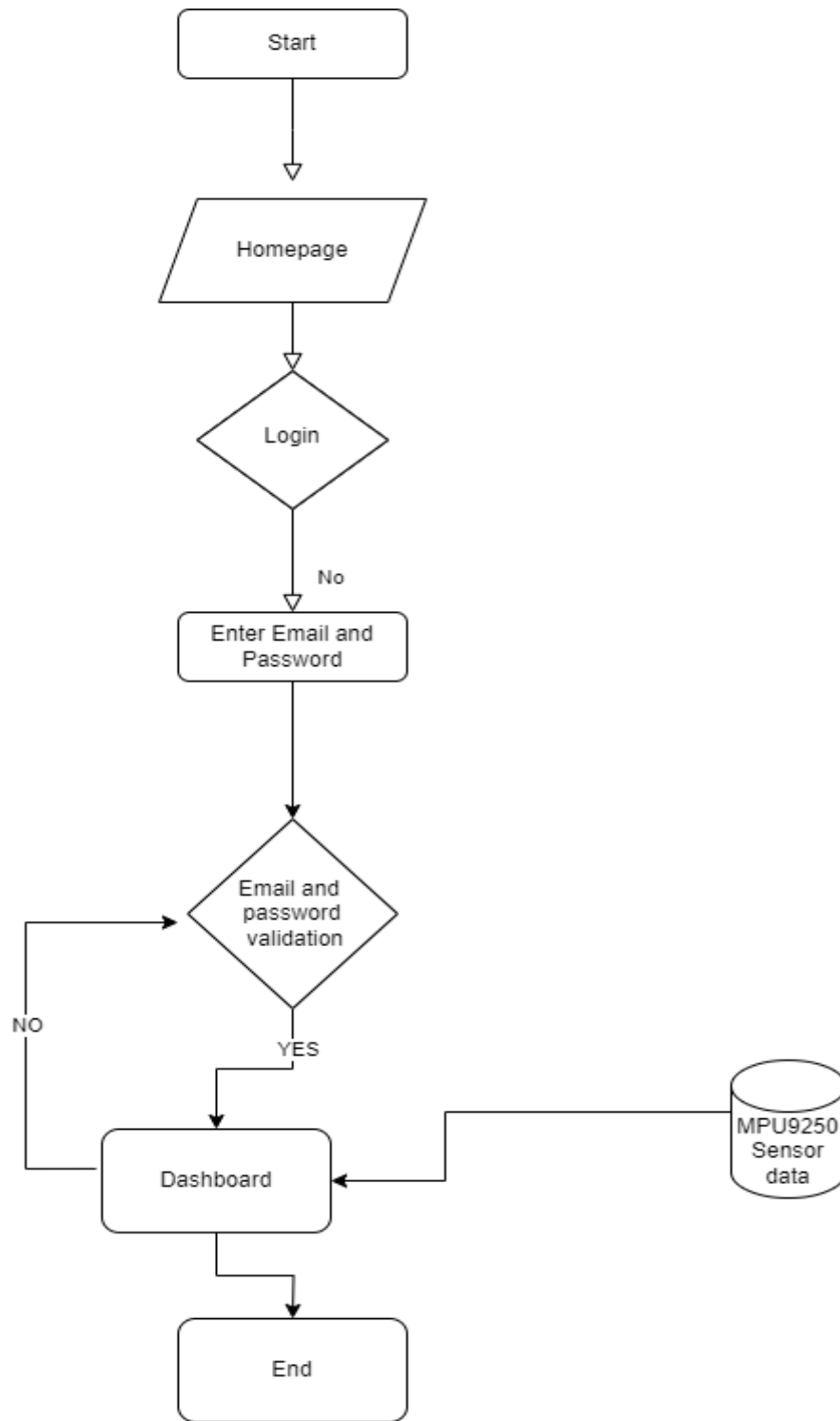


Figure 3. 11: System flowchart

## 3.2.2. Hardware and Software used in this Project

### 3.2.2.1. The hardware components used

#### 3.2.2.1.1. NodeMCU

NodeMCU (Figure 3.12) is an open-source firmware and development kit that helps to prototype IoT (Internet of Things) projects. It's based on the ESP8266 WiFi module, which allows to connect devices to the internet and communicate with other devices or servers. It is chosen in such a manner so that it can easily associate with Wi-Fi and hence finds its best use for remote monitoring applications. The ESP8266, designed and manufactured by Espressif Systems, contains the crucial elements of a computer: CPU, RAM, networking (WiFi), and even a modern operating system and SDK. That makes it an excellent choice for Internet of Things (IoT) projects of all kinds.

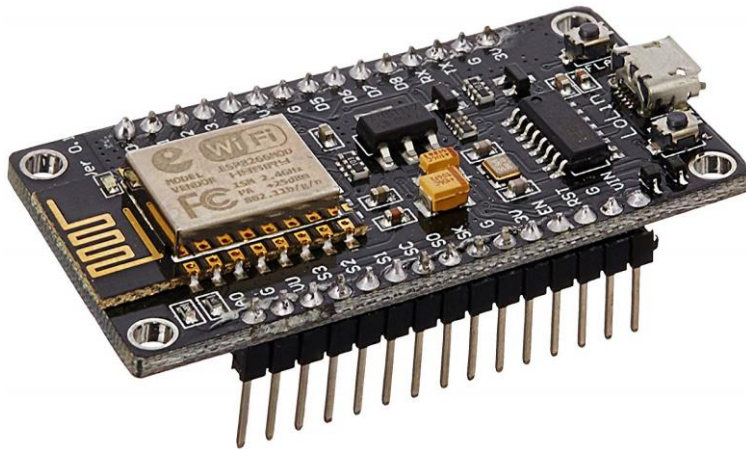


Figure 3. 12: NodeMCU

#### 3.2.2.1.2. MPU9250 sensor

The MPU9250 sensor (Figure 3.13) is a popular sensor module that combines a gyroscope, accelerometer, and magnetometer into a single chip. It's commonly used in various applications such as motion tracking, orientation sensing, and navigation. It is carefully selected based on criteria such as accuracy, precision, and compatibility with the NodeMCU platform for a gait monitoring system. The MPU9250 sensor is capable of measuring gait parameters such as step length, stance phase duration, and ankle flexion angle.

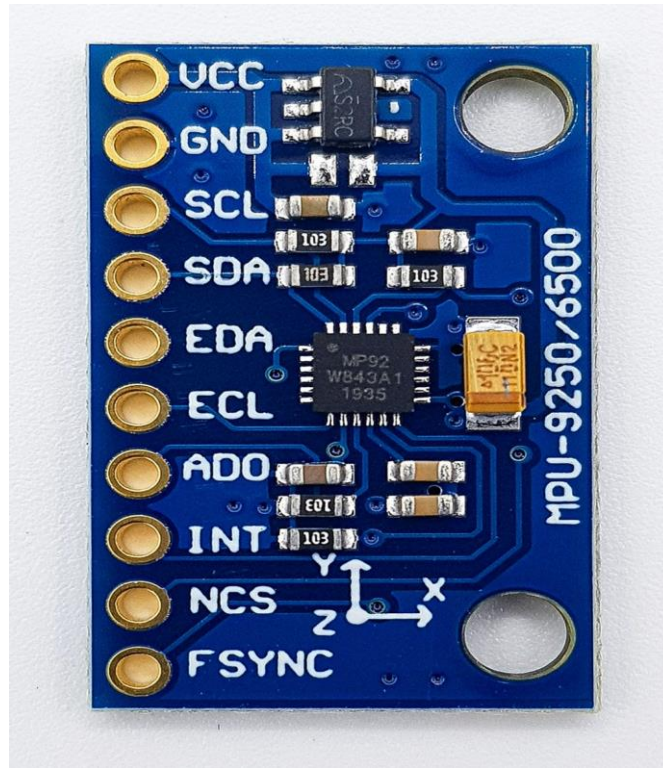


Figure 3. 13: MPU9250 sensor

### 3.2.2.1.3. Battery

A rechargeable lithium battery (3.7 V, 60 mA<sub>H</sub>–120 mA<sub>H</sub> (Figure 3.14)) power the NodeMCU to meet the operating input voltage requirements.



Figure 3. 14: Battery

### 3.2.2.1.4. Mini GSM/GPRS module

SIM800L (Figure 3.15) is a miniature cellular module which allows for GPRS transmission, sending and receiving SMS and making and receiving voice calls. Low cost and small footprint and quad band frequency support make this module perfect solution for any project that require long range connectivity.

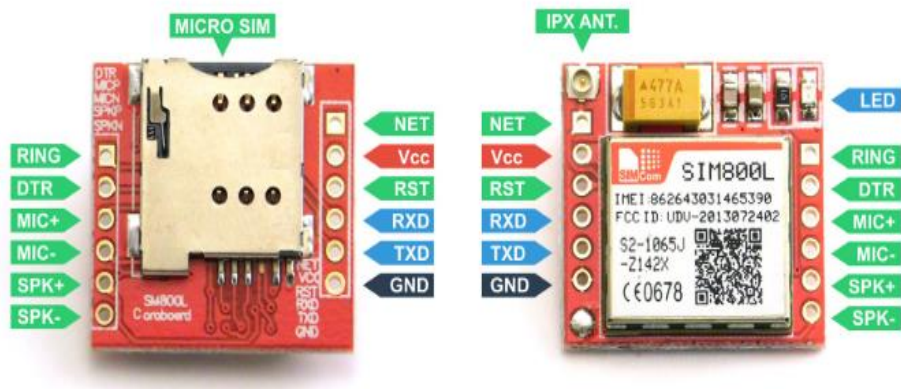


Figure 3. 15: Mini GSM/GPRS module

### 3.2.2.1.5. The LED (Light Emitting Diode)

A light-emitting diode ((Figure 3.16) LED) is a semiconductor light source that emits light when current flows through it. It has two pins such as cathode which is flat (negative) pin and anode which is longer (positive).



Figure 3. 16: The LED

### 3.2.2.2. The software used

#### 3.2.2.2.1. NodeMCU Firmware

This section describes how the firmware is developed in terms of the NodeMCU board, being programmed through the Arduino IDE and further configured to interface with MPU9250 so that

it collects the acquired sensor data and passes them to the server. Arduino IDE for NodeMCU is used to prototype firmware, develop sensor interfaces, and test information transmission protocols for our system.

#### **3.2.2.2.2. Server-side Software**

Develops server-side scripts with an application to receive, process, and store data from NodeMCU. Web dashboard presents details of the creation of a web dashboard using front-end technologies such as HTML, CSS and JavaScript. It covers the development of an interactive chart design for gait data visualization along with real-time updates on gait parameters. On server side, PHP language is used to handle all logic necessary and MYSQL database is used to store all the data sent by NodeMCU.

#### **3.2.3 Ethical consideration**

During the conduct of this project research, the following was observed. The researcher obtained ethical clearance from the College of Medicine and Health Sciences-Institution Review Board, as well as permission from the management of HVP Gatagara and Inkurunziza Orthopedic Hospital and the consent of respondents which granted him to conduct research. In addition, the autonomy of the patients was respected and granted with a right to withdrawal in the study at any time. Furthermore, Confidentiality was maintained by excluding the name of patient respondents from questionnaires. Finally, all collected data was kept in a secure place to which only the researcher was having access.

#### **3.3 Summary**

This research methodology chapter provides a detailed overview of the methods and approaches employed in developing a gait monitoring system for lower limb prosthesis users. By following a structured research methodology tailored to this project, we aim to ensure rigor, reliability, and validity in achieving the research objectives.

## CHAPTER 4. RESULTS

### 4.1 Introduction:

Here, there is a projection of an overview of the goals and objectives of the project which focus on gait monitoring system for a lower limb prosthesis user. It emphasizes on spatiotemporal gait parameter tracking such as **step length, stance phase duration, or ankle flexion angle** to assess mobility, efficiency in gait, or any problems that would cause deviations or abnormalities in any typical adults' prosthesis users.

#### 4.1.1. Formulas and calibration used to calculate spatiotemporal gait parameters

```
const float GRAVITY = 9.81; // Gravity in m/s^2

const float RAD_TO_DEG = 57.295779513082320876798154814105; // Conversion factor from
radians to degrees

const float THRESHOLD = 9.0; // Threshold for detecting stance phase (adjust according to your
setup)

// Calculate time difference

float currentTime = millis() / 1000.0; // convert milliseconds to seconds

float deltaTime = currentTime - previousTime;

// Calculate velocity by integrating acceleration

velocity += ay * deltaTime;

// Calculate displacement by integrating velocity

displacement += velocity * deltaTime;

// Calculate ankle flexion

float accelY = ay / 16384.0 * GRAVITY; // Convert raw acceleration to m/s^2

float totalAccel = sqrt(sq(IMU.getAccelX_mss()) + sq(accelY) + sq(IMU.getAccelZ_mss()));
```

```

float angle = acos(accelY / totalAccel) * RAD_TO_DEG;

float ankleFlexion = 90.0 - angle;

// Detect stance phase

if (accelY >= THRESHOLD && !isStancePhase) {

    isStancePhase = true;

    previousAccelY = accelY;

} else if (accelY < THRESHOLD && isStancePhase) {

    isStancePhase = false;

    stancePhaseDuration = currentTime - previousTime;

}

```

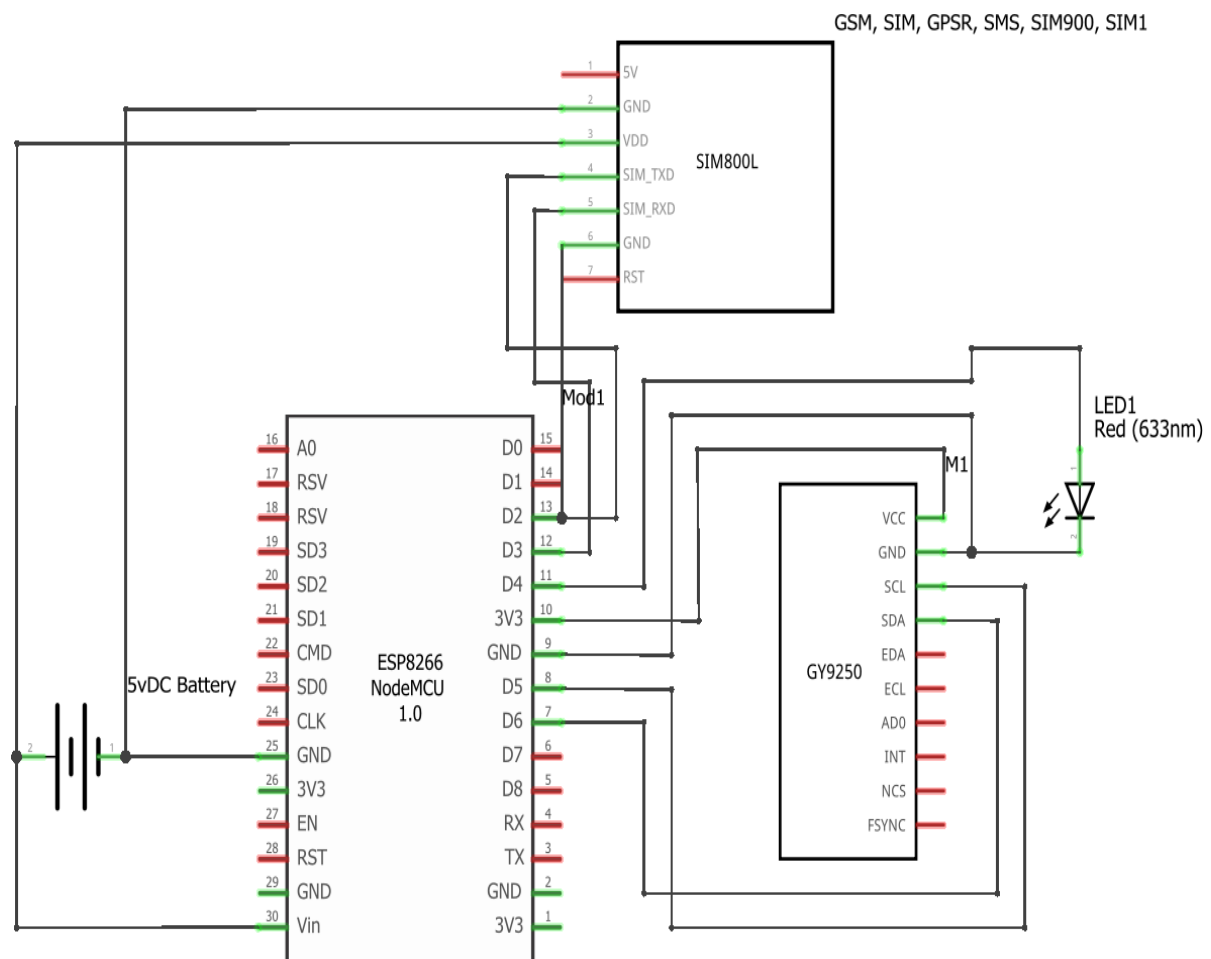
#### **4.1.2. The proposed sensing system circuit diagram**

The working principle of a gait monitoring system for lower limb prosthesis users involves several key components working together to provide accurate and real-time insights into the user's gait characteristics. The system utilizes an MPU9250 sensor for motion tracking, which is calibrated to ensure the accuracy of the collected data. The MPU9250 sensor employs gyroscopic, accelerometer, and magnetometer measurements, combined with sensor fusion techniques, to provide comprehensive motion tracking capabilities. Specifically, the sensor is utilized to detect parameters such as step length, stance phase duration, and ankle flexion.

For step length detection, the accelerometer data is analyzed to identify distinct patterns of acceleration corresponding to each step, allowing the system to determine the duration between consecutive steps. Stance phase duration is determined by measuring the accelerometer data during the period when the foot is in contact with the ground, indicating the start and end of the stance phase. Ankle flexion is estimated by analyzing the combined data from the gyroscope and accelerometer, particularly during the swing phase of the gait cycle.

Once the MPU9250 sensor collects and processes the data related to step length, stance phase duration, and ankle flexion, the NodeMCU board comes into play to transmit this data to a designated destination, such as a server or cloud platform. The NodeMCU board is responsible for interfacing with the MPU9250 sensor, collecting the processed data, and checking conditions to provide meaningful information about the data it receives.

Overall, by processing data from the MPU9250 sensor and transmitting it via the NodeMCU board, the gait monitoring system can provide valuable insights into the user's gait characteristics, which can help optimize the design and functionality of lower limb prosthesis users for improved mobility and comfort.



fritzing

Figure 4. 1: Sensing System Circuit Diagram

### 4.1.3. Data Acquisition and Processing:

The NodeMCU board is responsible for interfacing with the MPU9250 sensor to collect the processed data. It retrieves the measurements related to step length, stance phase duration, and ankle flexion from the sensor. Based on logic behind the program, the microcontroller will check the condition in Table 4.1 to provide meaningful information about the data it receives.

Table 4. 1: Normal and Abnormal Values for Step Length, Stance phase duration, and Ankle Flexion Angle

Parameter	Normal Values	Abnormal Values
Step Length	60-70 cm	< 50 cm, > 80 cm
Stance phase duration	60 – 80 %	< 50 %, > 90 %
Ankle Flexion Angle (Peak Swing Phase)	20-30 degrees	< 15 degrees, > 40 degrees

Once the data is acquired, the NodeMCU board utilizes its Wi-Fi connectivity capabilities to establish a connection with a cloud platform over the internet. This connection is established using HTTP as standard communication protocol. Before transmitting the data, the NodeMCU board may package the collected measurements into a structured format, such as JSON (JavaScript Object Notation), to ensure easy parsing and handling by the receiving end. Then the NodeMCU board sends the packaged data to the cloud platform. The NodeMCU makes an HTTP POST request to send the data to a designated endpoint on cloud as the NodeMCU board serves as the bridge between the MPU9250 sensor and the cloud platform, facilitating the transmission of gait parameter data collected by the sensor for further analysis, visualization, and monitoring.

### 4.1.4. Development of Web Dashboard

Now we are on the side of developing the web dashboard where visualizations have been made using charting libraries and made updated in real-time through server API integration.



Figure 4. 2: Interface of a Web Dashboard

## 4.1.5 Admin dashboard



Figure 4. 3: Dashboard showing gait parameters

### 4.1.6. Real-time Monitoring:

Real-time communication mechanisms such as WebSockets or Server-Sent Events are explained with a view to promptly updating the web dashboard. It has mechanisms whereby, in real time, users are to be alerted if any value for a gait parameter goes either above or below threshold values set by changing the received data from green to red color.

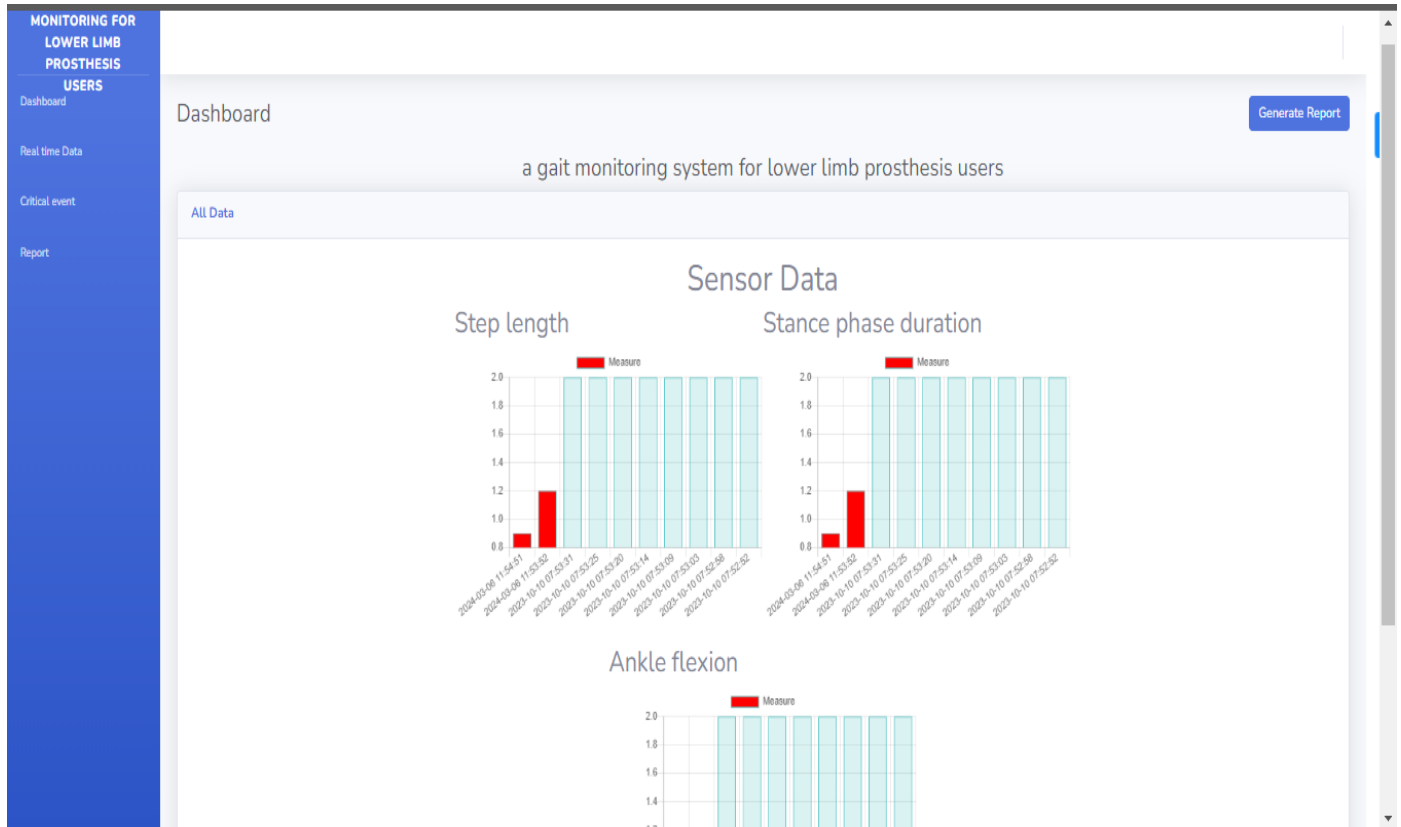


Figure 4. 4: Presentation of Sensor data in a web dashboard

#### 4.1.6. Parameter Thresholds and Alerts

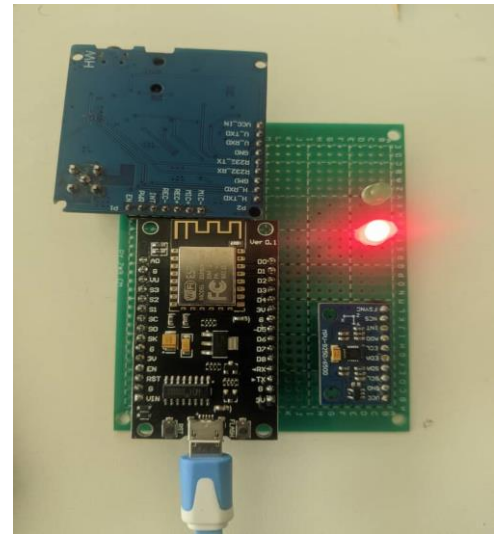
Define Normal and Abnormal Ranges: This will help provide guidelines for the definition of normal and abnormal ranges in gait parameters with respect to accurate threshold definition for an effective monitoring system.

#### 4.1.7. Alert Mechanisms

On the device there are Red and Green LEDs (Figure 4.7) that indicate the status of the patient where Red LED will be ON when one of these parameters is lying on abnormal range so as to inform the user about any deviation from accepted norms if such occurs, and hence guide the user with clear visibility by provision of both visual reminders as also alerts for immediate attention and Green LED to indicate normal conditions. We need also to communicate with clinicians that is why this device has ability to call and send SMS to the clinician to notify that the patient is not feeling well by using GSM module.



(a)



(b)

Figure 4. 5: Green LED is ON (a) indicating subject’s critical condition and Red LED is ON (b) indicating subject’s normal condition

#### 4.1.8. Report

The data is stored in database in structured way for future use as well as to help to detect the reason why a patient experiencing such complication. With this system, admin can download the PDF of all measurements sent by the sensor and if he/she would like to check only for critical condition he/she can get it. By clicking on word generate report in Figure 4.6, you can get all the data sent by sensor and the subject’s status in PDF so, you can make a deep analysis on what happened to that patient.

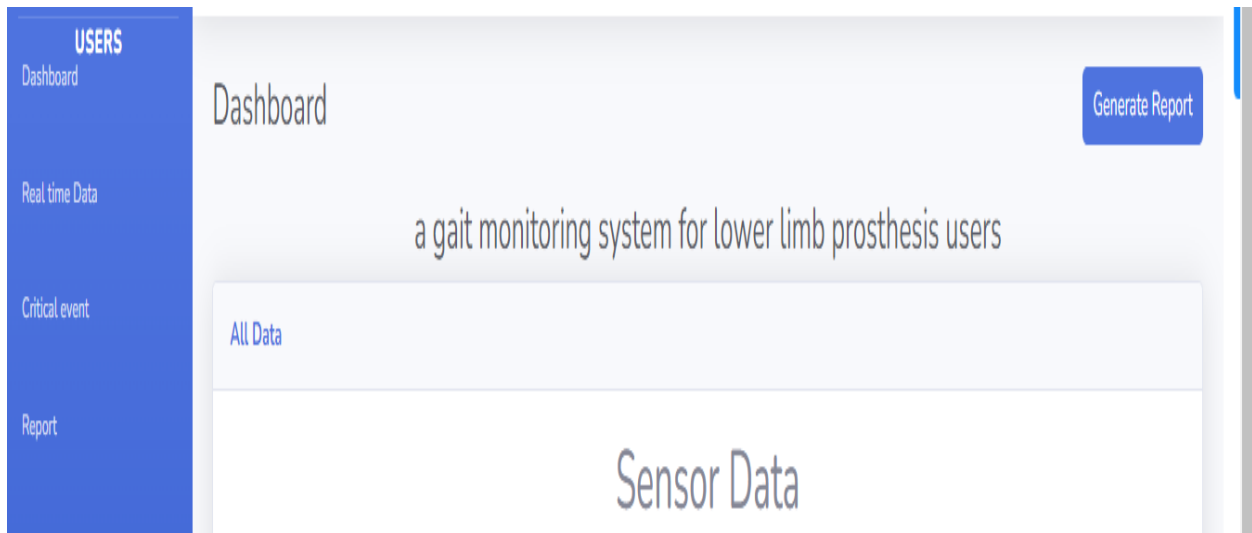


Figure 4. 6: The way of generating Report

#### 4.1.9. Results and Discussion

In this project, different tests were made to make sure that this device can track the critical condition in order to help us in calibration. Based on different testing we found that our device can measure step length, stance phase and Ankle of flexion angle.

Here are different samples from the sensor, and the controller can be able to detect abnormalities and send a notification through website and send SMS and call to the clinician.

#### Step length

As evidenced in Figure 4.8, the subject had abnormal step length when it is below 60 cm and beyond 80 cm, so, the chart becomes red so as to inform the clinician that the subject should be in danger if the problem persists and make a decision.

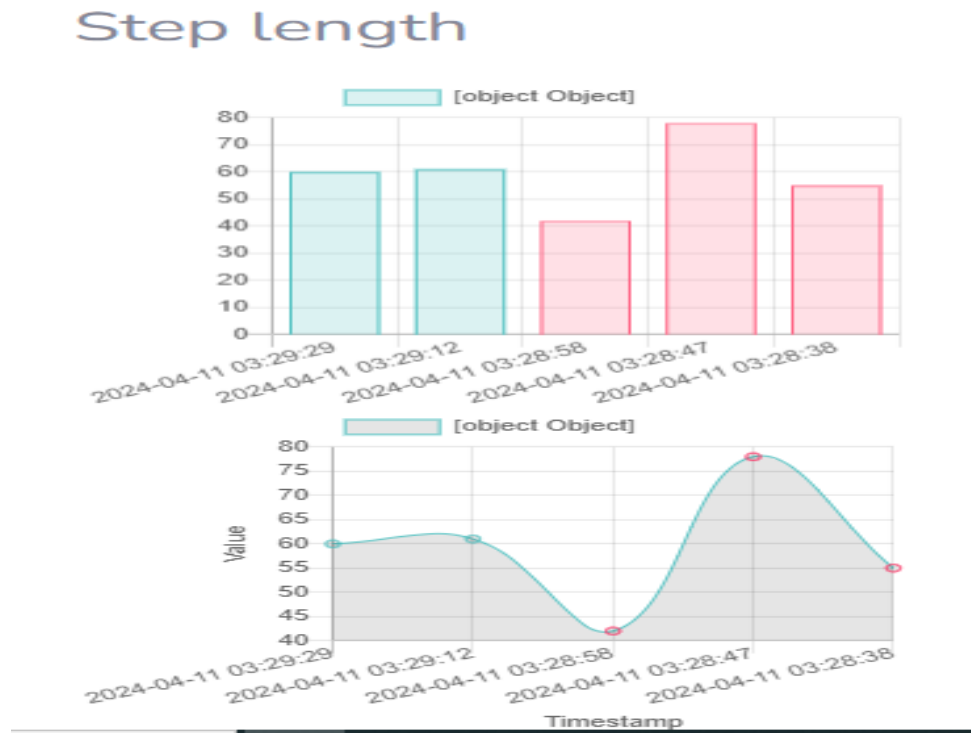


Figure 4. 6: Results of step length showing normal and abnormal statuses

## Stance phase duration

### Sensor Data Stance phase duration

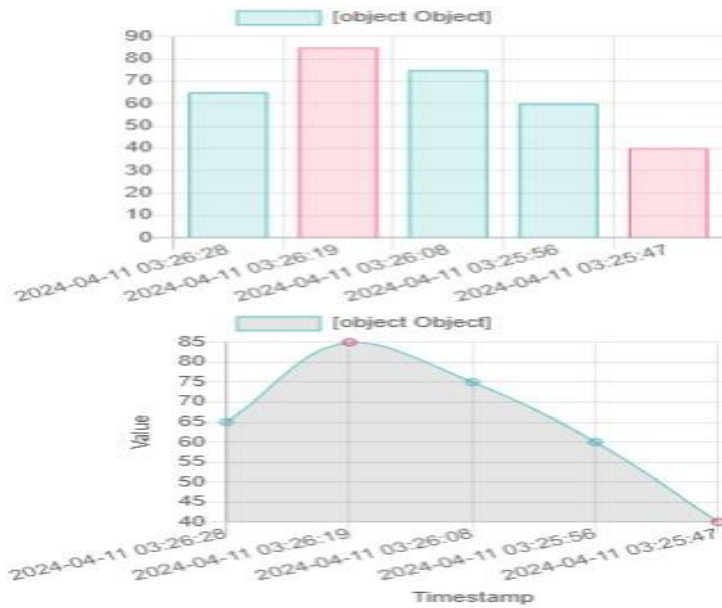


Figure 4. 7: Results of stance phase duration showing normal and abnormal statuses

## Ankle flexion

### Ankle flexion



Figure 4. 8: Results of ankle flexion showing normal and abnormal statuses

Table 4. 2: Results of testing the wearable device

Test	Step length (cm)	Stance phase duration (%)	Ankle of flexion (degrees)	Status
Test1	55	65	24	Good
Test 2	78	40	10	Bad
Test3	42	32	40	Bad
Test 4	61	72	25	Good
Test 5	60	63	28	Good



Figure 4. 9: Prototype of the device on a shoe cover

## **4.2 Summary**

In this chapter, the spatiotemporal gait during walking activities were studied. We have seen their deviation from the standard values as a sign of prosthesis deviation. If the stance phase duration deviates significantly from the typical range, it could indicate issues with gait pattern, prosthetic fit, alignment, or other factors. An excessively short stance phase might lead to instability and inefficient gait, while an excessively long stance phase might lead to discomfort, increased energy expenditure, or gait asymmetry. A longer single stance duration provides more time during which an ankle moment can be applied and allows for a larger centre of pressure shift. This suggests a larger ankle strategy contribution during slow as compared to normal steady-state walking. Further research into this topic would be beneficial in designing better prosthetic monitoring system and aid in the rehabilitation of the amputees.

## **CHAPTER 5. CONCLUSION AND RECOMMENDATION**

### **5.1 Conclusion**

This study presented the design and prototyping a gait monitoring system for lower limb prosthesis users. It tracks vital metrics including step length, stance phase duration, and ankle flexion by combining NodeMCU, mpu9250 sensor, GSM technology, and LED alerts. We made sure that everything was simple and accessible through careful design, which made it easier for consumers to incorporate into their regular routines. Timely feedback is provided by the LED notifications and SMS alerts provided by the system, encouraging ongoing participation and proactive gait parameter control. Furthermore, our system facilitates longitudinal analysis and customized rehabilitation programs by offering insightful information to researchers and healthcare providers. Although this method is a substantial improvement in gait monitoring for lower limb prosthesis users, more study might look at expanding gait monitoring and integrating machine learning algorithms for improved efficacy and user experience, which would ultimately lead too.

### **5.2 Recommendations**

To improve the gait monitoring system for lower limb prosthesis users, it is advised to expand parameter monitoring for a more thorough assessment, integrate machine learning algorithms for real-time gait analysis, and continuously incorporate user feedback and iterative design processes. The system's effectiveness and credibility will be further solidified by facilitating longitudinal data analysis, encouraging collaboration with healthcare providers, guaranteeing accessibility and affordability, and carrying out validation studies in real-world settings. Ultimately, these actions will improve rehabilitation outcomes and quality of life for people who wear lower limb prostheses.

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## APPENDICES

### Appendix 1: The Utilized Codes

```
#include <Wire.h>
#include <SoftwareSerial.h>

#define MPU9250_ADDRESS 0x68 // MPU-9250 default I2C address
#define LED_PIN 7 // Pin to which the LED is connected

//Create software serial object to communicate with A6
SoftwareSerial mySerial(3, 4); // A6 Tx & Rx is connected to Arduino #3 & #4

void setup() {
  Wire.begin();
  Serial.begin(9600);
  mySerial.begin(9600);
  pinMode(LED_PIN, OUTPUT); // Set LED pin as output

  // Initialize MPU9250...
  writeToRegister(MPU9250_ADDRESS, 0x6B, 0x00); // Power on MPU-9250
  writeToRegister(MPU9250_ADDRESS, 0x37, 0x02); // Enable bypass mode for magnetometer
  writeToRegister(MPU9250_ADDRESS, 0x24, 0x06); // Set magnetometer mode to continuous
mode
}

void loop() {
  // Read accelerometer and gyroscope data
  int16_t accel[3], gyro[3];
  readData(MPU9250_ADDRESS, 0x3B, accel, 3);
  readData(MPU9250_ADDRESS, 0x43, gyro, 3);

  // Estimate Step Length
  float accelX = accel[0] / 16384.0;
  float velocityX = integrate(accelX);
  float stepLengthX = integrate(velocityX);
```

```

// Estimate Stance Phase Duration
float stancePhaseDuration = estimateStancePhase(accel);

// Estimate Ankle Flexion
float gyroX = gyro[0] / 131.0;
float ankleFlexionX = integrate(gyroX);

// Print the results
Serial.print("Step Length (X-axis): ");
Serial.println(stepLengthX);

Serial.print("Stance Phase Duration: ");
Serial.println(stancePhaseDuration);

Serial.print("Ankle Flexion (X-axis): ");
Serial.println(ankleFlexionX);

// Check for abnormal values
if (stepLengthX < 50 || stepLengthX > 80 ||
    stancePhaseDuration < 0.8 || stancePhaseDuration > 1.4 ||
    ankleFlexionX < 15 || ankleFlexionX > 40) {
    alertDoctor();
    digitalWrite(LED_PIN, HIGH); // Turn on the LED
} else {
    digitalWrite(LED_PIN, LOW); // Turn off the LED
}

delay(2000);
}

float integrate(float value) {
    static float lastValue = 0;
    float integration = (value + lastValue) / 2.0 * 0.5; // Assuming a time step of 0.5 seconds

```

```

lastValue = value;
return integration;
}

float estimateStancePhase(int16_t accel[3]) {
    // Estimate stance phase duration based on changes in acceleration
    float accelX = accel[0] / 16384.0;

    static float lastAccelX = accelX;
    static bool inStancePhase = false;
    static unsigned long stanceStartTime = 0;
    unsigned long currentTime = millis();

    // Look for changes in acceleration along the X-axis
    if (accelX > lastAccelX && !inStancePhase) {
        // Detected start of stance phase
        inStancePhase = true;
        stanceStartTime = currentTime;
    } else if (accelX < lastAccelX && inStancePhase) {
        // Detected end of stance phase
        inStancePhase = false;
        unsigned long stanceDuration = currentTime - stanceStartTime;

        return stanceDuration / 1000.0; // Convert to seconds
    }

    lastAccelX = accelX;
    return 0.0; // Default value if stance phase is not detected
}

void readData(int deviceAddress, byte address, int16_t *data, int count) {
    Wire.beginTransmission(deviceAddress);
    Wire.write(address);
    Wire.endTransmission(false);
}

```

```

Wire.requestFrom(deviceAddress, 2 * count, true);

for (int i = 0; i < count; ++i) {
  data[i] = Wire.read() << 8 | Wire.read();
}
}

void writeToRegister(int deviceAddress, byte address, byte val) {
  Wire.beginTransaction(deviceAddress);
  Wire.write(address);
  Wire.write(val);
  Wire.endTransmission();
}

void alertDoctor() {
  // Send SMS and make call to the doctor
  send1(); // Send SMS to the first doctor
  call1(); // Make call to the first doctor
}

void updateSerial() {
  delay(500);
  while (Serial.available()) {
    mySerial.write(Serial.read()); // Forward what Serial received to Software Serial Port
  }
  while (mySerial.available()) {
    Serial.write(mySerial.read()); // Forward what Software Serial received to Serial Port
  }
}

void send1() {
  Serial.println("Sending SMS to Doctor 1...");
  mySerial.println("AT+CMGF=1"); // Configuring TEXT mode
  updateSerial();
}

```

```
mySerial.println("AT+CMGS=\"+250728551264\"); // Change with the phone number of the
first doctor
updateSerial();
mySerial.print("The patient's parameters are abnormal! Please check."); // Text content
updateSerial();
mySerial.write(26); // Send
}

void call1() {
  Serial.println("Making call to Doctor 1...");
  mySerial.println("ATD+250728551264;"); // Change with the phone number of the first doctor
  updateSerial();
  delay(20000); // Wait for 20 seconds
  mySerial.println("ATH"); // Hang up
  updateSerial();
}
```