CHAPTER-1

Introduction

Highlights of the Chapter

- *Identification of the problem*
- *Objectives and contribution of the thesis*
- *Outline of thesis organization*

According to the Census of India 2011, out of 121 crores, 2.68 crores population are disabled. Of these, 2.21% of the handicapped population, 20% of the disabled had a mobility impairment (Verma *et al.*, 2016). As shown in Figure 1.1, the movement disability is highest among all disabilities. Due to increasing urbanization, more and more people are suffering from lower limb amputations due to accidents or the spread of diabetes. If we look at the Census data of a newly developed state in India, Uttarakhand, primarily a hilly state, the movement disability is 20% among all kinds of disabilities (Figure 1.2).

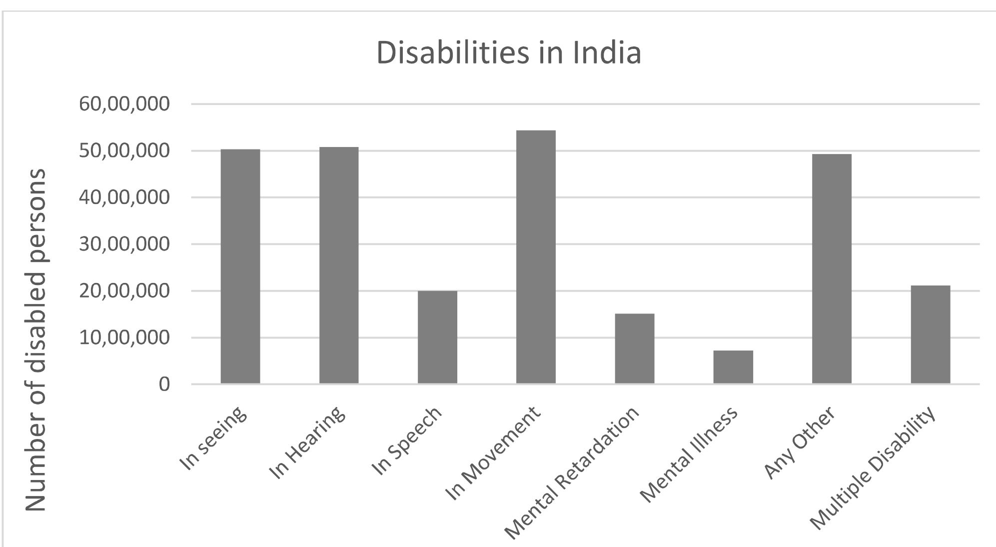

Figure 1.1 *Disabled population by type of disability in India (Census, 2011)*

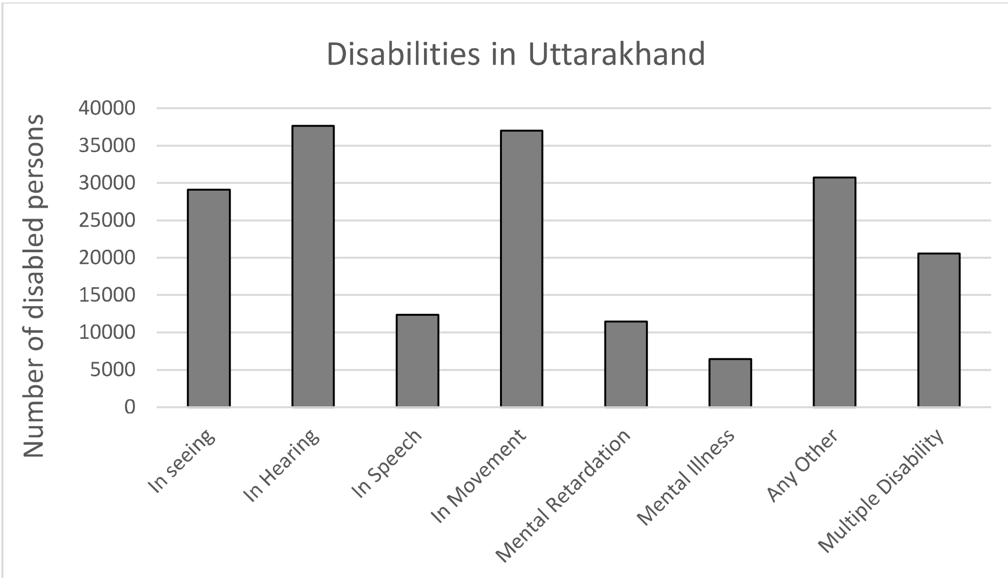

Figure 1.2 *Disabled population by type of disability in Uttarakhand (Census, 2011)*

In India, lower limb amputations account for 91.7% of traumatic amputations, of which 53% are transtibial amputations and 33% transfemoral amputations (Masum *et al.*, 2014). In developing countries such as India, where most of the disabled population is below average income, the development of low-cost lower-limb prosthetic devices still requires that they emulate healthy human mobility.

The present thesis identified the diagnosis of movement disability as an application because of its high demand in the densely populated developing country such as India. Orthosis and Prosthesis are two significant devices that are boon to such a disabled population. The term orthosis describes a device used to support a person with limb-impairment, whereas Prosthesis is used to replace a lost limb performing in succession with the residual limb (Tucker *et al.*, 2015). Further, the knowledge of human locomotion is necessary before designing a lower limb prosthetic device. A systematic and quantitative means to assess human locomotion is defined as Gait analysis. It includes measuring Spatio-temporal, Kinematics, Kinetics, and Electromyography (EMG) based parameters and their combinations. General gait parameters are the step length, stride length, step width, cadence, velocity, stance phase, swing phase, heel strike (HS) event, and toe-off (TO) event. Human gait analysis has a crucial role in sports, rehabilitation, clinical diagnosis, and healthcare monitoring. Therefore, the present thesis is also focused on designing and implementing a wearable gait analysis system.

1.1 Challenges in Gait Analysis

The standard approach to studying human gait has been utilizing a gait laboratory that most prominently includes image processing (IP) based system and floor sensors (FS) based system. Digital cameras, laser range scanners, infrared sensors, and Time-of-Flight (ToF) cameras are the commonly used devices in IP systems. In IP-based systems subject's gait information is captured by using one or more optic sensors. In FS systems, sensors are positioned along the floor. The gait data is acquired using pressure sensors and ground reaction force (GRF) sensors (Muro *et al.*, 2014). These sensors measure the force applied by the subject's feet on the floor when the subject walks. The above systems are standard means for gait analysis; however, the biggest challenge is that this is limited to a laboratory environment and is costly. It can be used for the validation of other alternate devices meant for gait analysis.

The alternate way to capture human gait data outside the laboratory during everyday activities is utilizing wearable sensors-based devices that use the sensors placed on the subject's feet, knees, and thighs. Accelerometers, gyroscopes, force sensors, electro-goniometers, and Electromyography (EMG) are commonly used sensors to detect the various signals that characterize human gait (Anwary *et al.*, 2018). The biggest challenge is during the initial study while acquiring the sensor data for gait analysis. The data needs to be recorded while a subject is walking in an open environment. Therefore, some reliable wireless setup is required during the initial phase of developing a wearable gait analysis device.

1.2 Challenges in Ankle-Foot Prostheses

The biggest challenge during the development of an ankle-foot prosthesis is that it must match the size and weight of the intact ankle. Also, it must provide a sufficiently large instantaneous power output and torque to propel an amputee. Another challenge is predicting gait-phase detection in real-time, which will be used in conjunction with the controllers to control MR damper and motor actuators. Other challenges are low voltage battery-powered, lightweight, high speed, and high torque motor actuators.

1.3 Objectives of the Thesis

The major objectives of the thesis are as below:

1. To develop a wireless wearable gait analysis setup to facilitate the simultaneous acquisition of Force-sensitive resistor (FSR) sensor-based foot insole data, Inertial measurement unit (IMU) sensors-based kinematic data, and Electromyography (EMG) sensors-based muscles activation pattern.
2. Classification of human foot movements using different Machine Learning (ML) and Fuzzy Logic Techniques.
3. Design a Tiny Machine Learning (TinyML) based embedded device to predict the amputee's intent for the movement of the ankle-foot Prosthesis.
4. Design and development of ankle-foot prosthesis prototype using magnetorheological (MR) damper and motor actuator.

1.4 Contribution of the Thesis

This thesis contributes to the necessary theory and implementation of real-time algorithms for human gait phase detection. The thesis has shown the following hardware and software developments:

1. Development of generalized hardware to acquire the simultaneous data from FSR, IMU, and EMG sensors.

2. Implement real-time gait phase detection techniques using thresholding, heuristic rule-based, and fuzzy logic in Arduino and Raspberry Pi environments.

3. Implementation of ML algorithms on Raspberry Pi and TinyML algorithms on Arduino Nano 33 BLE controllers to control the ankle-foot prosthesis movement in the sagittal plane.

4. Design prototype models for ankle-foot Prosthesis using Computer Aided Three-Dimensional Interactive Application (CATIA) CAD tool and its testing on ANSYS software for different foot positions.

The present work has tested and validated the algorithms on different male and female subjects. Further, the model prototype was tested on a transtibial amputee under a prosthetist's supervision for MR damper and motor actuator functioning for foot movement in the sagittal plane.

The advantages of the work presented in the thesis are:

1. The designed wearable gait analysis setup can acquire sensor data and simultaneous control of prosthetic devices.

2. The utilization of MR damper in the ankle-foot Prosthesis resulted in faster and variable stiffness during the locomotion.

3. The TinyML algorithms for EMG signals resulted in a real-time prediction of the amputee's intention for foot movement.

4. The utilization of Arduino Nano 33 BLE has resulted in faster performance, smaller size, enough memory to store the model or fuzzy rules, TinyML functionality, inbuilt IMU sensors, and best hardware interfacing capability in the real world.

1.5 Organization of the Thesis

The organizational structure of the thesis is as below:

Chapter 2 describes the literature review of gait phase detection techniques, lower limb prosthetic devices, and ML algorithms used in this work.

Chapter 3 presents different ML algorithms for the classifications of human locomotion in five different terrains using EMG and accelerometer on both legs.

Chapter 4 presents the simultaneous acquisition of FSR, IMU, and EMG sensors data and the implementation of real-time gait phase detection algorithms based on heuristic rules, zero-crossing and fuzzy logic techniques.

Chapter 5 compares EMG and Force-myography (FMG) signals to classify 6-foot movements using Raspberry Pi and Arduino Nano 33 BLE controllers. It also describes the fuzzy logic control using the Arduino platform to classify foot movements. It further utilizes TinyML for the real-time control of ankle-foot Prostheses.

Chapter 6 presents the design and development of the ankle-foot prosthesis prototype. It also describes the testing of a model using ANSYS software. The chapter describes the use of two major controlling parts to control MR damper and motor actuator.

Finally, Chapter 7 concludes the thesis work and highlights the future work that might interest further research.