CHAPTER-2

Theoretical Background

Highlights of the Chapter

- *Gait analysis*
- *Wearable sensors for gait analysis*
- *Understanding of gait phase detection techniques*
- *Role of gait analysis in biomedical engineering*
- *Overview of lower limb prosthetic devices*
- *Machine Learning Techniques*

This chapter presents the literature review about gait phase detection techniques using different sensors. The chapter explains the usefulness of gait analysis in different fields; the major focus in realizing the prosthetic foot to mimic human locomotion. This chapter also briefs the literature survey about different types of prosthetic foot in the market. Various ML algorithms are also introduced, applied to the signals acquired from healthy and amputee subjects for pattern recognition tasks in later chapters.

2.1 Gait Analysis and Gait Phase Detection Techniques

Walking is an important action in humans' day-to-day life. Its systematic study is termed gait analysis (Whittle, 2014). It is broadly divided into stance and swing phases. These are further segmented into more moving phases: initial contact (IC), loading response (LR), midstance (MST), terminal stance (TST), pre-swing (PSW), initial swing (ISW), mid-swing (MSW), and terminal swing (TSW) (Tao *et al.*, 2012). Gait analysis is the systematic investigation of human locomotion. Human gait analysis has been carried out in two different ways: (i) through wearable sensors-based devices and (ii) non-wearable sensors-based devices sensors (Muro *et al.*, 2014). In non-wearable sensors-based gait analysis, gait analysis is performed in the laboratory, where the subject walks on a marked walkway. Using wearable sensors-based devices, it is possible to capture human gait data outside the laboratory during everyday activities. Non-wearable sensors-based devices can be classified as image processing (IP) based systems and floor sensors (FS) based systems. In IP-based systems subject's gait information is captured by using one or more optic sensors. Digital cameras, laser range scanners, infrared sensors, and Time-of-Flight (ToF) cameras are the commonly used devices in IP systems. 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 wearable sensors-based devices use sensors placed on the subject's feet, knees, and thighs. Accelerometers, gyroscopes, force sensors, electro-goniometers, active markers, and Electromyography (EMG) are commonly used sensors to detect the various signals that characterize human gait (Anwary *et al.*, 2018).

Following terms have been used regarding literature collection: gait analysis, gait phase detection, gait events detection, lower limb prosthesis, below-knee prosthesis, ankle-foot prosthesis, biomechanics, inertial measurement unit (IMU), acceleration, gyroscope, Kinect sensors, foot insole sensors, Ground level walking, stair ascent walking, stair descent walking, ramp ascent walking, ramp descent walking, wearable sensors, EMG, Wireless sensor network, Machine learning, Magnetorheological (MR) damper. Tables 2.1 and 2.2 show previous papers' analysis in the following two areas: gait analysis using camera-based methods and gait analysis methods based on wearable sensors, including IMU and foot insole sensors.

Table 2.1 *Summary of Gait Analysis Survey using Camera and Image Processing*

Authors	**Highlights of Study**	**Remarks**
Rocha *et al.*, 2018	Automatic gait analysis using RGB-D camera (Kinect v2) and multilayer perceptron algorithm	The data acquired from fifteen subjects and tested on 5 subjects. Results showed an overall accuracy and F1 score of 98%.
Li *et al.*, 2018	Classification of gait disorder due to Parkinson and Hemiplegia neuro-degenerative diseases using Kinect sensor-based motion trajectories	The limitation of the method is the low resolution of the data acquisition that hampers representation and recognition of subtle motions.
Munoz *et al.*, 2018	Gait analysis using wavelets and a Kinect camera	Results showed the identification of the Parkinson's disease or healthy subjects with 93% accuracy.
Massalin *et al.*, 2017	Intent recognition for lower-limb prostheses using Depth camera (DS 325, Softkinetic) and support vector machine	Results from four subjects showed that the SVM classifier with no dimension reduction resulted in 94.1% accuracy for five activities: standing, walking, running, stair ascent and stair descent.
Zou *et al.*, 2017	Robust gait recognition using the combination of inertial and RGBD (color and depth) sensors	50 subjects' datasets resulted in the effective gait recognition. However, for enhanced gait recognition, the system requires more sensors and more effective classifiers.
Yang *et al.*, 2016	Human gait tracking using 3-Kinect v2 sensors	Only few frames with small time delays were observed; however, none of them cause incorrect results.
Ye *et al.*, 2016	Motion capture analysis using single depth camera	Results are presented for the rehabilitation walking exercise in the sagittal plane with a mean error of at most 1.75% in detecting gait events;

		however, the overall framework should also be tested for frontal view motion analysis.
Andersson *et al.*, 2014	Human gait detection using Kinect sensor- based skeleton data, Machine learning (kNN and MLPNN) models.	Authors used flexion peaks and extension valleys from the lower joint's rotation angles for calculating the position of each gait cycle in each walk. A single gait cycle provides a poor performance, however, adding more than 4 to 5 gait cycles resulted in better correct classification rate.
Wang and Liu, 2007	Gait recognition based on positioning human body joints	Authors used a nearest neighbor classifier to classify and recognize subjects with the best classification rate of 85%.
Zhao *et al.*, 2006	Multiple camera-based 3D gait recognition	Local optimized algorithm-based tracking is presented that can deal with the effects of viewpoint and surface variations, which are difficult to solve with 2D analysis.
Roy *et al.*, 2004	Gait characteristic detection using image processing technique	Pressure distribution pattern under foot during walking is used to compare normal and abnormal gait patterns.
Wang *et al.*, 2003	Gait analysis using statistical shape analysis	Background subtraction technique is used to segment silhouettes. Results showed the better recognition performance for frontal viewing angle (90°) than lateral (0°) and oblique (45°) angles.
Riener *et al.*, 2002	Camera-based gait analysis for stair ascent and stair descent	Camera-based optoelectronic system is used for gait kinematics and joint moments and powers were computed

		at different inclination angles using inverse dynamics.

Table 2.2 *Summary of Gait Analysis Survey using Wearable Sensors/IMUs/Foot Insole Sensors*

Authors	**Highlights of study**	**Remarks**
Godiyal *et al.*, 2018	Overground and ramp gait event detection using Force myography-based system.	A heuristic approach was developed for the subject-specific and terrain-independent model to determine HS and TO in a gait cycle. The results were reported for healthy subjects; however, the algorithm is yet to be tested on amputees.
Anwary *et al.*, 2018	Gait asymmetry identification using wearable sensors.	An Android App was used to collect real-time synchronous IMU data from legs. The total distance, time, velocity, stride, step, cadence, step ratio, stance, and swing parameters were obtained.
Jiang *et al.*, 2018	Gait phase-detection system using Force myography	Force myography band resulted in above 99% accuracy for classifying four gait phases using the LDA classifier.
Allseits *et al.*, 2018	Knee angle estimations for gait monitoring	Knee joint angles were obtained from lower limb angular velocity measured using two gyroscopes mounted in a leg.
Kim and Lee, 2017	IMU-based foot-ground contact detection (FGCD)	Results demonstrated the detection of four subphases of stance phase, i.e., HS, FC, HO, and TO, irrespective of the walking speed

		and walking terrain. However, there was a 60ms time delay during TO detection for the stair ascent.
Ryu and Kim, 2017	Real-time gait subphase detection using EMG signals	The results showed that for the signal graph matching (ESGM) algorithm, the average detection latency was 5.5 times lower than another method.
Maqbool *et al.*, 2016	Gait event detection for the control of lower limb prostheses	The results showed that the time differences in identifying Initial Contact (IC) and Toe Off (TO) events were larger in a transfemoral amputee when compared to healthy subjects and a transtibial amputee.
Botzel *et al.*, 2016	Gait analysis for the detection of initial and terminal contact	A correlation was conducted between the data collected using various sensors and a motion capture system for 14 healthy male subjects.
Chen *et al.*, 2016	Human gait kinematic analysis for rehabilitation	The SVM classifier provided an accuracy of 94% for the data acquired using force-sensitive resistors attached insole and triaxial accelerometer.
Gouwanda and Gopalai, 2015	Real-time gait event recognition using wireless gyroscope	The authors proposed an algorithm by combining the heuristics rules and the zero-crossing method to identify HS and TO at an average time of 100 ms.

Bejarano *et al.*, 2014	Gait events detection using two inertial and magnetic sensors placed on the shank	An ambulatory real-time gait phase-detection system was developed and compared with existing algorithms. The model achieved an F1 score of 1 for healthy subjects and 0.98 for stroke subjects.
Gorsic *et al.*, 2014	Wearable sensors-based gait phase detection	A simple heuristic rule-based technique was tested on three amputees using a robotic prosthesis controlled by a finite-state controller and compared with HMM. Results showed a >90% successful detection rate for all four phases.
Bae and Tomizuka, 2013	Tele-monitoring system for gait rehabilitation	The measurements of GRFs from the shoe insole were used to estimate the gait phases, which, in turn, were utilized as zero-velocity periods for the estimation of foot position.
Howell *et al.*, 2013	Kinetic gait analysis using force-sensitive resistors-based insole	The GRF and ankle dorsiflexion/ plantarflexion moment were measured using an insole, and the results were correlated with the motion laboratory measurements; the %RMS errors were under 10%.
Yun *et al.*, 2012	Human foot motion estimation using Inertial and magnetic sensors	The algorithm estimated the foot position by estimating the foot orientation, velocity, acceleration, and gait phase measured using inertial/ magnetic sensors. The achievable position accuracy of

		the algorithm is about 1% of the total walked distance.
Yang *et al.*, 2012	an accelerometer-based gait analysis system	An analysis software (iGAIT) was developed in MATLAB to visualize gait parameters acquired using accelerometer sensors, where the data can be recorded with sample frequencies ranging from 5 Hz to 200 Hz.
Lee and Park, 2011	Quasi-real-time gait event detection	The algorithm is the modification of the algorithm presented by Aminian and Najafi (2004). Validation results showed that the algorithm detected the end contacts -8ms prior and the initial contacts with a delay of 19ms when compared with footswitches.
Huang et al., 2008	Strategy for locomotion mode identification using sEMG signal	For 8 healthy subjects, the average classification errors obtained to classify four-gait phases were 12.4% ± 5.0%, 6.0% ± 4.7%, 7.5% ± 5.1%, and 5.2% ± 3.7%, respectively.
Bamberg *et al.*, 2008	Gait analysis using wireless sensors system	GaitShoe was built to be worn in any shoe, capable of detecting heel-strike and toe-off, as well as estimating foot orientation and position.
Sabatini *et al.*, 2005	Walking features assessment using a biaxial accelerometer and a gyroscope	Root-mean-square errors less than 0.18 km/h (speed) and 1.52% (incline) were reported for tested speeds in the intervals [3, 6] km/h

		and inclines in the intervals [5, +15]%.
Aminian and Najafi, 2004	human motion analysis using body-fixed sensors	Accelerometers and angular rate sensors-based hybrid sensors were proposed to measure the 2D kinematics of a body segment through simple biomechanical models.
Aminian *et al.*, 2002	Measurement of Spatio-temporal gait parameters	The medio-lateral rotation of the lower limbs, the stride length, and velocity were estimated by integrating the angular velocity. The errors reported for the velocity and stride length estimations are 0.06m/s and 0.07m, respectively.
Pappas *et al.*, 2001	Reliable gait phase detection using a rule-based algorithm	The results showed detecting the gait phase events within a time delay of 90ms.

In prosthetics, instrumented gait analysis offers higher understandings and knowledge of the various adaptive mechanisms for human gait with a prosthesis (Rietman *et al.*, 2002). Aminian *et al.* (2002) have described an ambulatory system using gyroscopes for estimating Spatio-temporal parameters during the walk. Two pairs of FSR have been used as footswitches for assessing the accuracy of measurements. Wavelet analysis is used to compute temporal gait parameters during the gait cycle from the lower limb's angular velocity.

Pappas *et al.* (2004) have presented a gait-phase detection sensor (GPDS) in combination with a programmable functional electrical stimulation (FES) system. This is aimed at the subjects having dropped-foot walking dysfunction. The instrumented GPDS insole consists of a tiny gyroscope to measure the angular velocity of the foot, and 3- FSR sensors are attached on foot- one at the heel and two at metatarsal bones. It acts as two-state switches indicating the presence of weight. These are used in a finite state control scheme to time the electrical stimulation sequences. By combining insole and FES systems has resulted in a substantial development in the artificial leg gait-kinematics.

Sabatini *et al.* (2005) have devised a gait phase segmentation technique by integrating IMU to determine off-line temporal gait parameters using MATLAB. The authors have employed the second-order LP Butterworth filter for sensor signals (accelerometer signal cut-off frequency: 17 Hz; gyroscope signal cut-off frequency: 15 Hz). Lee and Park (2011) have developed a quasi-real-time detection algorithm for gait event detection using shank-attached gyroscope signals.

A novel online gait phase detection algorithm has been studied and evaluated by Muller *et al.* (2015). They have used 3D accelerometers and 3D gyroscopes, and an algorithm is designed for arbitrary orientation of the sensor and auto adjustment to the current pace. Khandelwal *et al.* (2016) have proposed an algorithm for accelerometer by using expert knowledge (EK), i.e., the prior knowledge of walking gait characteristics in combination with continuous wavelet transform (CWT) to detect (heel-strike) HS and toe-off (TO) gait events. Wavelet transform-based algorithm provides instantaneous time-frequency analysis of a non-stationary signal and has been shown to be powerful for peak detection.

Gouwanda and Gopalai (2015) have proposed a gait phase classification technique supported by neural networks using robotic lower limb attached sensor signals. They acquired gyroscope data from foot and shank and used the algorithms based on heuristics and zero-crossing methods for gait event detection. The zero-crossing method is used to identify potential points that may correspond to mid-swing (MSW), HS, and TO.

Heuristics are resulting from the features of the shank angular rate signal to evaluate potential points. The first derivative of angular rate is used for monitoring zero crossings, which correspond to a potential MSW, HS, and TO. The corresponding angular rate will be recorded as a potential point when a zero-crossing or a sign change is detected. Finally, a set of heuristics are used to evaluate these potential points to determine the related gait events.

Maqbool *et al.* (2016) have presented an approach for real-time gait event analysis for level ground and ramp activities for lower limb amputees with a shank attached - wireless gyroscope. They have used footswitches as a validation means for both healthy people and amputees. They showed that the identification of IC and TO took a larger time in a transfemoral amputee (TFA) than a healthy and transtibial amputee (TTA). In another study, Zakria *et al.* (2017) used a rule-based method for detecting gait events based on the use of a single gyroscope attached to the shank.

2.2 Usefulness of Gait Analysis

Analysis of the gait phase can provide valuable insights about neurological conditions like Parkinson's disease that directly affect an individual's motor functions. Gait analysis approaches based on FSR, and IMU sensor data help to detect neurodegenerative diseases. Parkinson's disease is a common neurodegenerative disorder that primarily affects the elderly population. Primary symptoms of Parkinson's disease include stiffness or rigidity of arms, trembling, slowness of movement, and unstable posture (Zesiewicz, 2019).

Gait analysis has shown promising results in open environments, and it provides proper observation of an individual's day-to-day gait characteristics like step length, step time, walking time, total steps, and stride length. These characteristics can provide intricate details of an individual's overall gait process (Del *et al.*, 2016). A detailed study on using such free-living sensors to evaluate gait characteristics and falling risk in older people is given in (Weiss *et al.*, 2013). The older people wore body sensors for three days and carried out their routine work. The recorded data were analyzed, and the readings were found to help evaluate fall risk.

Gait analysis also aimed at the subjects having dropped-foot walking dysfunction. Mechanical brace (called AFO) is a conventional method to treat drop-foot. Blaya and Herr (2004) have presented a gait active ankle-foot orthosis (AAFO) where the impedance of orthotic joint is controlled during stride for analyzing drop-foot gait. Technological improvements have led to the growth in numerous wearable devices for the physical support and restoration of human locomotion. Tucker *et al.* (2015) have studied different methods to control compact powered lower limb prosthetic and orthotic (P/O) devices. The term orthosis describes a device used to support a person with limbs-impairment, whereas a prosthesis is used to replace a lost limb- so this performs in succession with the residual limb.

2.3 Lower Limb Prosthetic Devices

Amputation is a surgical procedure to remove a part or limb from a body. Figure 2.1 shows the types of lower limb amputations. As the names suggest, amputations performed lower the hip are termed as lower-limb amputations (LLAs). LLAs include the amputation of toes, ankle, and the entire leg. LLA can be categorized as above-knee (AK) and below-knee (BK) amputation. AK amputation is also termed transfemoral amputation. It is a surgical procedure accomplished to remove the limb above the knee joint. The BK amputation is also named transtibial amputation. Here the limb below the knee is removed. The other types of LLAs include partial foot amputation, ankle disarticulation, through-knee amputation, and hip disarticulation. The prosthesis is a resolution for amputees to bring back function and increase the quality of life after amputation (Kumar *et al.,* 2017).

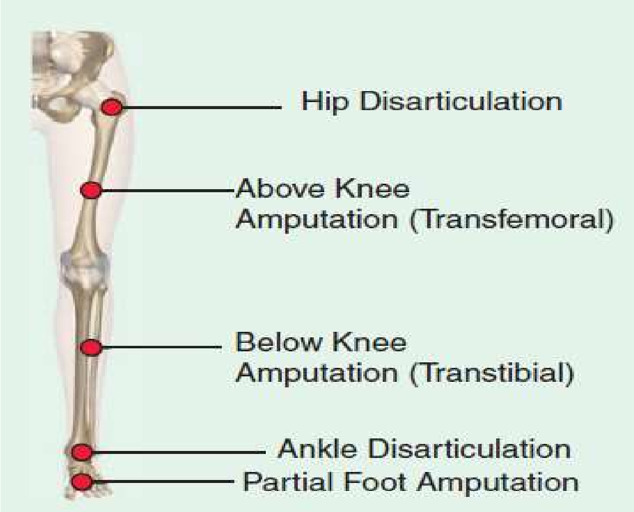

Figure 2.1 *The types of lower limb amputations (Kumar et al., 2017)*

A BK prosthesis consists of a socket, pylon, and foot. However, an AK prosthesis comprises a knee unit in addition to that of a BK prosthesis. Both are shown in Figure 2.2.

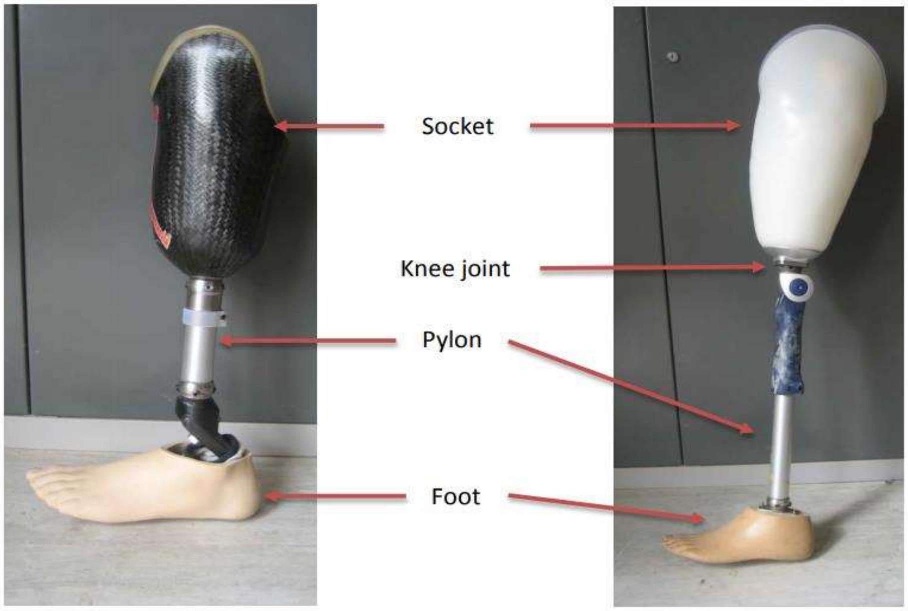

Figure 2.2 *Below-knee vs. Above-knee Prosthesis*

The Socket

A socket joins the prosthesis with the user and transfers the amputee's weight to the ground using other prosthetic components. A socket must meet the following critical issues: fit, comfort, and suspension. As a result, it is essential to develop lightweight materials for rugged sockets, with the mechanical properties the same as that of bone, to provide an equal stress distribution in the amputated region.

The Knee

The skeleton's joints determine how the body moves and what it can do. The knee joint is the most complicated prosthetic system. The knee is a load-bearing joint that allows for smooth motion and stability during walking, sitting, kneeling, and squatting. The pylon (the part of the leg below the knee) and the socket of the prosthesis are connected by the knee. The knee is divided into single-axis and multi-axis joints in kinematics. Due to its simple structure, a single-axis knee is considered the most basic knee. It has a single centre of rotation that functions similarly to a door hinge. It is the smallest, lightest, and most durable alternative available, as well as the most cost-effective due to its simplicity, but it lacks stance control. A four-bar mechanism is used in a multi-axis, also known as a polycentric knee. These knee joints can be constructed to be stable during the stance phase and flex easily during the swing phase since they have several axes of rotation.

The Pylon

The pylon is a component that connects the knee to the foot and distributes an amputee's weight to the floor via the foot. Pylons are typically made of steel to provide high mechanical strength and rigidity. The pylons are hollow pipes to reduce the total weight of the prosthesis. Aluminum alloys are utilized to make pylon since they are lighter than steel.

The Foot

The foot is the final component that transfers the weight to the floor. The traditional prostheses used nowadays are the solid ankle cushion heel (SACH) foot and the stationary attachment flexible endoskeletal (SAFE) foot. SACH and SAFE foot cushion and absorb energy, but they do not store or return the same amount of energy. The articulated single-axis foot has an ankle joint that allows the foot to move up and down, improving knee stability, favoring users who prioritize stability. A multi-axis foot can move from side to side and is equivalent to a single axis foot in terms of weight, durability, and cost. This allows the user to better conform to uneven surfaces. A dynamic reaction foot is an advanced foot that can collect and release energy while walking. The wearer gets a subjective impression of push-off, a better range of motion, and a more symmetric gait than conventional feet because of the store-and-release feature.

Lower limb prostheses can be categorized into - mechanically passive devices, microprocessor-controlled passive devices, and powered devices. Passive and microprocessor-based prostheses perform relatively well while walking on the ground level. However, there is a limitation that they cannot produce positive energy during some activities like stair ascent. Powered prostheses employ active actuators to produce joint torque that drives the knee and ankle joints. In the present research, the objective is to present a powered ankle-foot prosthesis prototype. Table 2.3 shows the summary of different mechanisms used for the control of the prosthetic leg.

Table 2.3 *Summary of the survey on prosthetic leg controls*

Authors	**Highlights of study**	**Remarks**
Spanias *et al.*, 2018	Robotic lower limb prosthesis	The subject's intent was identified using neural information through various electro-mechanical sensors. The adaptive pattern

		recognition system showed an accuracy of 96.3%.
Pandit *et al.*, 2018	Insole-sensor-based transfemoral prosthesis	A passive prosthesis was designed using a magneto-rheological (MR) damping system for transfemoral amputees.
Shultz *et al.*, 2018	Powered ankle prosthesis controller	A behavioral model was framed for the human ankle by gathering the data from the healthy subjects, which were later applied as controller behaviors for a powered prosthesis prototype.
Culver *et al.*, 2018	Powered ankle prosthesis controller	The control system was designed for a transtibial prosthesis and evaluated on a single unilateral transtibial amputee. The designed powered prosthesis provided desirable stair ascent and stair descent capability relative to the passive prosthesis.
Nordin *et al.*, 2018	Transtibial prosthetic limb with MR damper	A simulation-based study was conducted using MR Damper with a Fuzzy-PID controller. The implemented system showed better performance to reduce the vibrations.
Ficanha *et al.*, 2014b	Cable-driven ankle-foot mechanism	A prototype cable-driven ankle mechanism was designed for two controllable DOFs in

		dorsiflexion-plantarflexion and inversion-eversion directions.
Caputo *et al.*, 2014	Ankle–foot prosthesis emulator for human locomotion	A tethered ankle-foot prosthesis was presented using a powerful electric motor and a low interference transmission. The ankle provided 14deg to 17deg (dorsiflexion) and 35deg to 27deg (plantarflexion) for unloaded to maximally loaded condition.
Chen *et al.*, 2014	Adaptive slope walking using a robotic transtibial prosthesis	A myoelectric controller was used along with an intrinsic controller in a robotic transtibial prosthesis for adaptive slope walking, where the intrinsic controller provides the control output according to the walking slope.
Mitchell *et al.*, 2013	Ankle-foot prosthesis with delayed release of plantarflexion	This study showed the effect of delayed plantarflexion on subjects having lower-limb loss. A dc motor is used to take up and hold the compression of a carbon-fiber ankle joint. Lengthening the impulse from the foot resulted in comfortable for a user.
Wang *et al.*, 2013	Echo-based gait phase analysis for lower limb prosthesis	The result showed that according to the motion information and echo

		relationship between the prosthesis and the sound limb, the gait phase of a prosthetic limb could be established from the sound side.
Wang J. *et al.*, 2013	Ankle plantar flexion control in a powered transtibial prosthesis	Powered plantar flexion minimizes the impact on the leading leg at heel-strike. Proportional EMG control of powered plantar flexion provides users the benefit of volitional control over their prosthesis during mid to late stance.
Jamal, 2012	Prosthesis circuit design considerations	EMG signal acquisition has been presented here. Due to its non-invasiveness, SEMG proves to play a significant role in rehabilitation prosthesis.
Ha et al., 2010	Volitional control of prosthetic knee	The results showed that average rms trajectory tracking errors of the prosthetic knee using the EMG-based volitional control and the intact knee of the 3 subjects were 6.2◦ and 5.2◦, respectively.
Eilenberg et al., 2010	Powered ankle-foot prosthesis control using a neuromuscular model	An adaptive muscle-reflex controller was presented based on simulation studies that utilize an ankle plantar flexor comprising a Hill-type muscle

		with a positive force feedback reflex.
Alimusaj et al., 2009	Kinematics and kinetics study of an Adaptive ankle-foot	The increased dorsiflexion of a Proprio-Foot (prosthetic ankle) improved the knee kinematics and kinetics of transtibial amputees during stair ambulation.
Au et al. et al., 2008	Powered ankle-foot prosthesis	Myoelectric-driven and finite-state controllers resulted in a more biomimetic ankle response, producing net propulsive work during level-ground walking and greater shock absorption during stair descent than the conventional passive-elastic control method.
Vrieling et al., 2008	Study of uphill/downhill walking for unilateral lower-limb amputees	Gait velocity and lower limb joint angles were measured in the motion analysis laboratory. Uphill and downhill walking can be trained in rehabilitation, which may improve the safety and confidence of amputees.
Varol et al., 2008	Gait mode intent recognition approach for the supervisory control of a powered transfemoral prosthesis	Gaussian Mixture Models classifier and PCA dimension reduction with 100 sample-long frames provided the best results for standing and walking mode recognition.

Meléndez-Calderón et al., 2007	An online simulation tool for lower-limb prosthetic devices	Lower-limb Amputee Simulator (LLAS) was built using Working Model 2D and MATLAB. This tool was used to control a Fuzzy Controller designed for an active transfemoral prosthesis.
Au et al., 2005	Active ankle-foot prosthesis	Biomimetic EMG-controller demonstrated a smoother and more natural movement pattern than the neural network approach, suggesting that a biologically-motivated, model-based approach is advantageous for controlling an active ankle prosthesis.
Blaya and Herr., 2004	Active ankle-foot orthoses	Orthotic joint impedance was modulated for drop-foot gait treatment in two subjects. The study showed the reduced slap foot occurrence, and ankle kinematics closely resembled healthy subjects during the swing phase.
Hansen *et al.*, 2004	Inferences for the design of biomimetic ankle prostheses	Non-disabled human ankle joint characteristics were observed for their implications in the design of ankle prostheses. The results suggested that a spring-damper system may be used to effectively mimic the human ankle for slow to normal

		walking speeds if the damper's effect is reduced to zero as the speed approaches normal speeds.

Cain *et al.* (2007) designed powered ankle-foot orthoses for plantar flexion assistance during walking using two control methods- footswitch (a kinematic control) and proportional EMG signal from the soleus (a physiological control). These two methods are shown in Figure 2.3. The authors preferred proportional myoelectric control over footswitch control due to more significant metabolic savings.

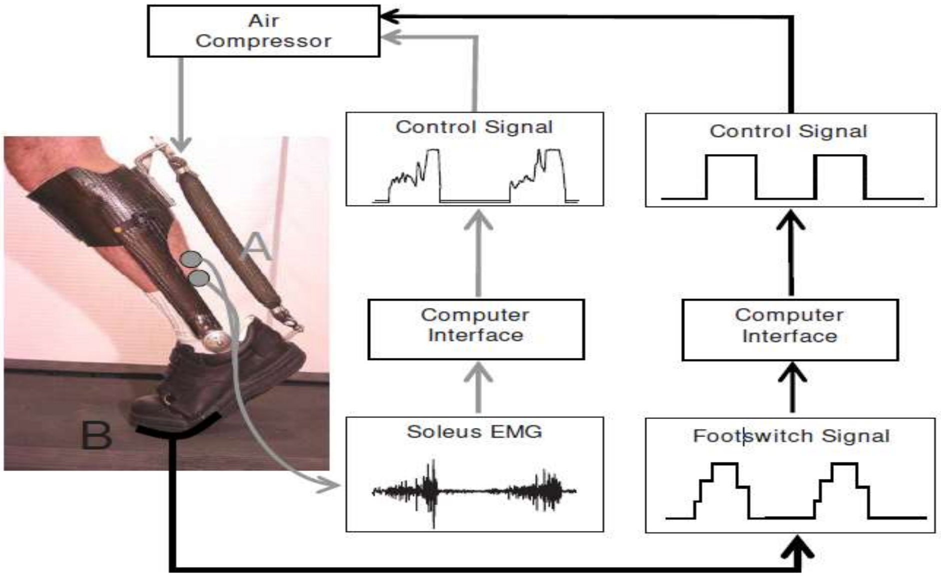

Figure 2.3 *Two orthosis control methods: proportional EMG control and footswitch control (Cain et al., 2007)*

Au *et al.* (2008) have developed and evaluated the finite-state controller for a powered ankle-foot prosthesis driven by the myoelectric signal. The prosthesis employs both sensory inputs measured from the prosthesis and myoelectric signals detected from residual limb muscles. Torque, impedance, and position controllers are the three basic low-level servo controllers required to mimic ankle behavior. Ankle angle, torque, and foot contact pressure are the local variables for state detection and transition. Two finite-state controllers are used to get biomimetic gait patterns for level-ground and stair descent strides. Myoelectric signals acquired from tibialis anterior and gastrocnemius muscles have been used as control commands during stance for switching between these two finite-state controllers. This prosthesis is proficient for variable impedance during the stance phase, similar to a normal human ankle.

Latif *et al.* (2008) have designed a low-cost prosthesis for above-knee amputees, as shown in Figure 2.4. Here the limited rotational movement of the knee joint is regulated by voluntary myoelectric signals acquired from two opposing thigh muscles for leg flexion/ extension. The amplitude of the muscle signal usually varies from less than 1 μV to 10 mV, and the instrumentation amplifier (TL074 IC) is used for amplification. They have used an active 10.23 Hz (40-dB/decade) high pass Butterworth filter cascaded with a passive 3.18 kHz low pass filter. A 12V, 3W servo motor is used for driving the prosthesis.

The purpose of recent prosthetics is to imitate the role of the substituted limb or body part most professionally and sensibly possible. Spring Ankle with Regenerative Kinetics (SPARKy) project started with the aim of creating full able-bodied (AB) ankle function to transtibial amputees, mainly those injured while serving for the military (Bellman *et al.*, 2008). The first regenerative ankle, SPARKy-1, is proved to store and release 16 J of energy per step. SPARKy-2 is lighter and more powerful than the previous version using a roller-screw transmission and a robust brushless DC motor. SPARKy-3 is a two- DOF device capable of providing high power for running and jumping activities. Figure 2.5 shows the designs of SPARKy-1, 2, and 3.

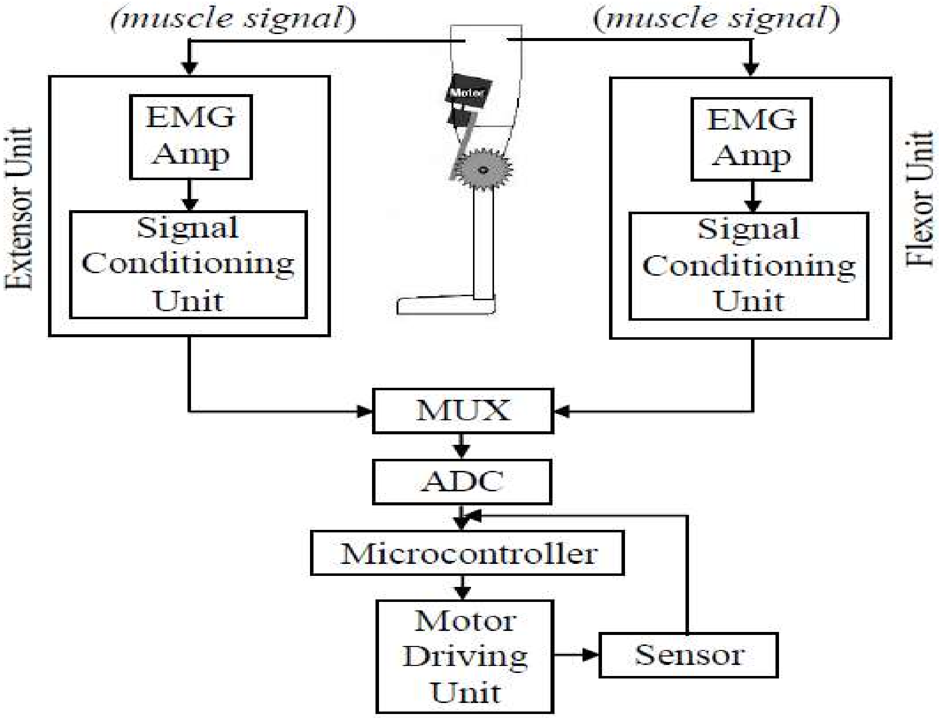

Figure 2.4 *Block diagram of the prosthesis system (Latif et al., 2008)*

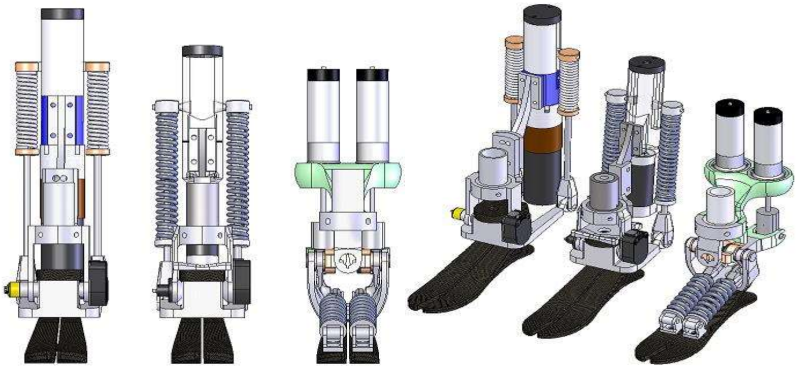

Figure 2.5 *The three designs of SPARKy-1, 2, and 3 (Bellman et al., 2008)*

The biological limb produces significant net power over a stride in several locomotive tasks. In the deficiency of net power production, TFA wearing passive prosthesis have shown to spend 60% more metabolic energy when compared with healthy subjects during level walking. Sup *et al.* (2008) have presented a general idea for designing and controlling an electrically powered knee and ankle prosthesis. Their design contains two motor-driven ball screw units to push the knee and ankle joints. A spring parallel to the ankle motor unit has been employed to decrease the power consumption and increase the torque output for given motor size. An ankle prosthesis by utilizing a semi-active damping mechanism has been presented by LaPre and Sup (2011) for active slope adaptation. Authors have studied the TTA's biomechanics for an initial step onto a 10-degree inclined and declined slopes from level ground. By utilizing this data, a model of an adaptive-ankle (including a spring foot in series with an adjustable damper) is presented.

Zhu *et al.* (2010) have proposed a power-driven ankle to substitute the AB ankle that can deliver adequate power to thrust the body upward and forward during bipedal locomotion. For making amputees walk additional steady and natural, they have used segmented- foot with toe joints in a prosthesis. The segmented foot makes the amputees effort-saving by decreasing the torque of the ankle. Two series elastic actuators (SEA) drive the ankle and toe joints that offer enough torque and build it shocks tolerant. Angle sensors, touch sensors, and force sensors are included in a prosthesis, and the sensory system can sense and feedback the position and torque of the joints in real-time. The experimental results show that the powered compliant ankle and segmented foot prosthesis can be easily used for gait rehabilitation.

A microprocessor-controlled prosthetic foot has been developed by Collins and Kuo (2010). It arrests collision energy usually dissipated by the leg and "recycles" it as positive ankle work. The energy-recycling prosthetic foot contains the following component groups: attachment interface, toe assembly, heel assembly, primary compression spring, heel clutch, and toe latch. As the heel contacts the ground, starting a gait cycle, the rear-foot section rotates and compresses a coil spring. At extreme compression, the rear foot is latched by a continuous one-way clutch. Instead of discharging the spring energy suddenly, the foot stores it until an adequate load is detected on the forefoot.

A finite-state control approach for a powered below-knee prosthesis has been presented by Yuan *et al.* (2011) using ankle and toe. They have designed a powered prosthesis with power-driven joints and segmented foot (PANTOE-1) for below-knee amputees' level ground (LG) walking. The prototype and CAD model of PANTOE-1 is shown in Figure 2.6. Authors have used two contact switches for heel strike and toe strike, two 1000N force sensors to assess the exerted pressure by ground at heel and toe, two round-potentiometers for ankle angle and toe angle, one linear- potentiometer positioned parallel to ankle spring for measuring the displacement of spring and estimating ankle torque.

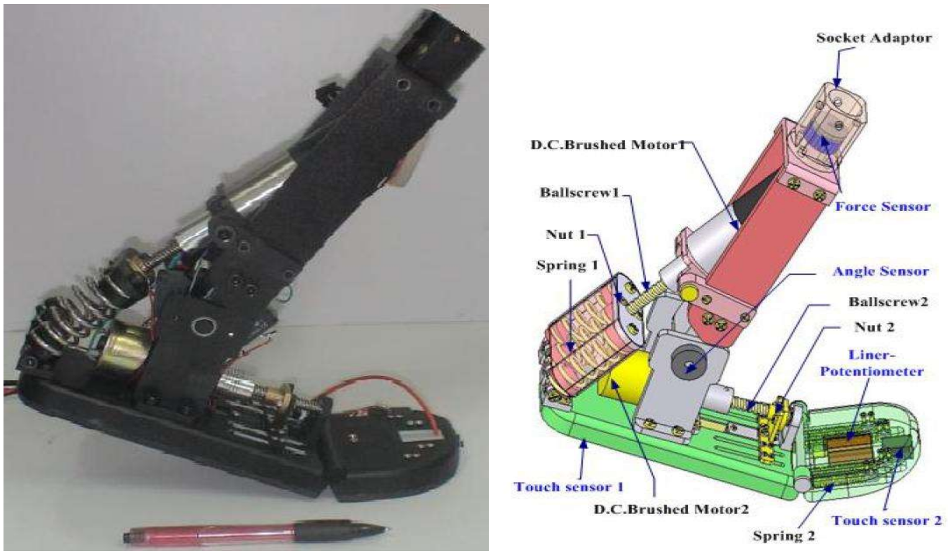

Figure 2.6 *The prototype and CAD model of PANTOE-1 (Yuan et al., 2011)*

Grimmer *et al.* (2012) have studied distinct types of elastic actuators that are used to calculate peak power (PP) and energy requirements (ER) for copying human ankle behavior. They have found that PP and ER are reduced in the SEA, parallel elastic actuator (PEA), and SE+PEA in contrast to a direct drive (DD). A parallel element will drop PP more than a serial element; however, serial elements benefit from lowering ER more than a parallel element. Grouping of serial and parallel components might offer further benefits in PP; however, it reduces the advantages in ER in contrast with a single serial element. The mechanically adjustable compliance and controllable equilibrium position actuator (MACCEPA) has been reported as a comparatively soft variable-stiffness actuator (VSA) with nonlinear series-elastic properties.

Herr and Grabowski (2012) presented a bionic prosthesis that imitates the function of the human ankle while walking on LG, explicitly delivering the net positive work essential for a range of ambulatory velocities. The bionic ankle produces net positive work by employing a battery instead of metabolic energy. Therefore, the amputees wearing bionic prostheses have experienced normative ankle mechanics and push-off exertion in their trailing leg. Cherelle *et al.* (2012) proposed an energy-efficient powered transtibial prosthesis imitating human ankle behavior, called ankle mimicking prosthetic (AMP)-Foot 2.0. Researchers have used two springs; the former is known as plantarflexion (PF) spring for accumulating energy from the dorsiflexion phase. Another spring is called push-off (PO) spring, where the actuator injects energy into the spring during the whole stance phase. The energy stored in the PO spring is kept using a locking system before heel-off, and the energy is released for push-off. In this manner, it is likely to lessen the actuator's power while delivering the full torque required for thrust during walking.

Spanias *et al.* (2018) have presented a powered lower limb prosthesis that is designed to get the user's neural data and kinetic/kinematic data using attached mechanical sensors. They have collected EMG data and the mechanical sensor data from amputees by utilizing a power-driven knee/ankle prosthesis for various walking actions like level ground walk, stair ascend/descend, and ramp ascend/descend. EMG signals are acquired from residual extremity muscles and can be fed as input to a pattern recognition algorithm that can flawlessly change over the prosthesis between the above ambulation actions. First, data is gathered to train an adaptive forward predictor algorithm while subjects were finishing related mode transitions. Next, it determines whether the adaptive algorithm can automatically update EMG model parameters utilized by the forward predictor during walking activity.

A robotic intelligent prosthetic limb named Adaptive Modular Active Leg (AMAL) has been built at the IIIT Allahabad using an MR damper that controls the knee movement of an amputee (Nandy *et al.*, 2012). Pandit *et al.* (2018) have discussed a lower extremity prosthesis to allow normal gait kinematics for TFA utilizing magneto-rheological (MR) damping and electronic control system. They have positioned sensors on the plantar insole to deliver knowledge for normal gait kinematics, thus enabling the control of the current in the MR damper throughout the different phases of a stride. The MR damper is a highly advanced shock absorber whose damping can be precisely adapted at a much faster rate (in few milliseconds). The MR damper is filled with magneto-rheological fluid. When MR fluid is subjected to a magnetic field, the tiny-sized magnetic particles bring into line according to the magnetic force line and change into a viscoelastic solid. This fast damping has motivated me to include the MR damper in the design of powered ankle-foot prosthesis that microcontrollers can control.

2.4 Machine Learning Techniques

There is a growing interest in the automatic identification of gait types from gait features. It's essential to seek ways to analyze the information acquired by cameras and/ or wearable sensors fitted around the subject. Machine learning (ML) has become a popular means for evaluating such knowledge that reflects the behavioral features of humans. The purpose of ML methods is to construct algorithms that study either from experience as the labeled data or search automatically for helpful patterns from data points provided (Prakash *et al.*, 2018). ML models are mainly divided into supervised and unsupervised types of models. A definite target value must be presented in the supervised learning model, whereas one does not focus on the target value or class label in the unsupervised models. Supervised Learning includes multilayer perceptron neural networks (MLPNN), k- nearest neighbor (KNN), support vector machine (SVM), radial basis function (RBF), random forest, decision tree, etc. Fuzzy k-mean, hierarchical clustering, self-organizing map (SoM) are examples of unsupervised or clustering methods.

ML is a rapidly advancing field that finds applications in solving complex problems and can do the same with little or no human intervention. In machine learning, the computer learns through experience, similar to how humans learn (Jordan and Mitchell, 2015). ML is a subset of AI that allows the machine to learn from past data to give accurate results with minimal human intervention. Another popular technology, Deep learning (DL), is a subset of machine learning that uses neural networks. One of the most demanding application areas of AI and ML is robotics, which has proven effective in repetitive jobs that may lead to mistakes or accidents and other jobs that individuals may find degrading. In the current scenario, machine learning is slowly becoming an integral part of human lives. Many devices and software extensively use machine learning to facilitate complex tasks. Table 2.4 lists various ML techniques used in this research work along with their brief description.

Table 2.4 *Machine Learning Classifiers*

Classifier Name	**Description**	**Reference**
Linear Discriminant Analysis (LDA)	Linear Discriminant Analysis (LDA) is a dimensionality reduction technique used to reduce the dimensionality of data for faster computation and analysis.	(Fisher, 1936)
Logistic Regression (LR)	Logistic regression is a simple ML algorithm that predicts the probability of a target variable. It is a type of supervised learning algorithm and can be applied to solve various problems like spam detection, disease prediction, and financial forecasts.	(Cox, 1958; Menard, 2002)
Gaussian Naïve Bayes (NB)	The core basis of all Naïve Bayes (NB) classifiers is Bayes' Theorem. It measures the conditional probability of an event occurring in conjunction with the occurrence of another event.	(Rish, 2001; Caruana and Niculescu, 2006)
K- Nearest Neighbors (KNN)	The k-nearest neighbors (KNN) algorithm is a simple, supervised machine learning algorithm applied to classification and regression problems. KNN finds the distance between the given point and the point in the dataset. K number of closest points are selected, and the most frequent label is voted. In the case of regression average of labels is taken. KNN computes the Euclidean distance between two points.	(Cover and Hart, 1967)
Support Vector Machine (SVM)	The core of the support vector machine (SVM) is to find a distinct hyperplane (decision boundaries) to classify points. This hyperplane should have a high distance or margin between data points of both classes. A high margin between the points ensures accurate	(Cortes and Vapnik, 1995)

	classification of unseen data points later. The data points proximal to the hyperplane that affect its positioning and alignment are called support vectors. This leads to the division of the data into distinct classes.	
Decision Tree (DT)	A decision tree (DT) classifier is a common algorithm that involves generating a tree to obtain a decision or prediction. Nodes represent each feature, and each decision rule is represented by branches. Root and internal nodes contain test conditions to distinguish the records.	(Quinlan, 1986)
Random Forest (RF)	The core idea behind the random forest (RF) classifier is constructing an ensemble model consisting of multiple DT. Every tree generates predictions, and the process of voting selects the final prediction. Due to the collection of various models, the final accuracy is much higher than individual models. This is achieved as each tree performs independently of each other's.	(Ho, 1995)
Ensemble Techniques	The Ensemble technique combines multiple classifiers to form a new classifier that performs better than all constituent classifiers. The main aim of an ensemble classifier is to reduce variance and bias. When multiple classifiers are combined, despite having weak performances individually, they perform much better.	(Opitz and Maclin, 1999)
Neural Networks (NN)	The central idea behind an artificial neural network (ANN) is to mimic the biological neurons and nervous system. As the neurons have multiple connections through synapses, an ANN consists of connected units that transmit signal/data to other neurons. The neurons are arranged into layers, with each layer	(Wang, 2003; Basu *et al.*, 2010)

	specializing in a distinct function. The nature of transformation achieves this that each node applies to the data.	

ML techniques have been widely used for gait assessment through the estimation of spatio-temporal parameters. In a gait classification application to elderly, post-stroke and Huntington's disease patients, Mannini *et al.* (2016) used a SVM classifier to discriminate the abnormal gait patterns. In the past work, researcher used LDA with principal component analysis (PCA) and uncorrelated linear discriminant analysis (ULDA), KNN, and multilayer perceptron neural network (MLPNN) with back propagation algorithm (Negi *et al.*, 2016, 2017, and 2018) for the myoelectric control of upper limb prostheses. Jung *et al.* (2015) proposed a gait phase classification method based on neural networks by acquiring sensors data from lower limb exoskeleton robots. Pattern recognition is the frequently used control approach for powered prostheses. Surface electromyography (sEMG), mechanical sensors (IMUs, load sensors, and pressure-sensitive insoles), or a fusion-based control are helpful for lower limb activity recognition. Lemoyne and Mastroianni (2019) used DT, KNN, LR, and SVM classifiers for regulating the powered prosthesis during gait. The aim of the present research is to find the most suitable classifier for real-time classification of human foot movement and to implement a standalone computing system supporting TinyML for ankle-foot prosthesis control.

2.5 Performance Metrics for Machine Learning Classification

To evaluate the performance of neural network some metrics or measures of performances are required. In this section the common performance metrics are briefly discussed. The results of a classifier are divided into 4 categories:

True Positives (TP) are when the data point's actual class was True and the predicted class was True as well.

True Negatives (TN) are when the data point's actual class was False and the predicted class was also False.

False Positives (FP) are positive classes predicted by the model, but they are False.

False Negatives (FN) can be interpreted as the model predicted negative class, but it is False.

Accuracy is one of the most common evaluation metrics in classification tasks. It is defined as the total number of correct predictions divided by the total number of predictions made for a dataset. Accuracy is practical when the target classes are balanced. Since, the data is imbalanced in reality; in order to obtain a complete picture of the model, other metrics should also be considered. Precision is the ratio of True Positives to all the positives predicted by the model. Recall (Sensitivity) is the ratio of True Positives to all the positives in your Dataset and the F1-score is a measure that combines Precision and Recall and equals the harmonic mean of both. To visualize the performance of the classifier a confusion matrix is created based on the 4 parameters explained above.

2.6 Conclusion

This chapter highlighted the literature review on the gait analysis using different sensors and the applicability of gait analysis for prosthetic ankle-foot design. This chapter also presented the literature survey about different types of prosthetic foot. Apart from this the various ML algorithms were also introduced briefly, and the literature survey was performed on the role of ML in gait analysis and the control of prosthetic devices.