CHAPTER 1

INTRODUCTION

With the onset of industrialization and advancement in technology the pace of life has increased rapidly. So has man’s work pressure, resulting in avoidable accidents. Many causalities happen because of road and machine accidents etc, in which large number of humans lose their limbs. Some of these accidents are so fatal that the individual is crippled for life. Often the loss of a limb is non-reversible. To add to man’s agony, wars and terrorist strikes have done their bit as have silent killers like diabetes etc. Generally, the amputations take place in upper body extremities (above and below elbow amputations) and lower body extremities (above and below knee amputations). Above knee amputation is referred to as transfemoral amputation, while below knee is called transtibial amputations. According to estimates, there are incidences of over 40 thousand leg amputations in India annually. The scenario is even worse in developed countries like the US with an annual incidence of 1.25 Lakhs lower extremity amputations. India is a developing country with agriculture as a main source of generating income. Many persons are working as farmers and labors and any kind of amputation whether above extremity or below extremity makes one’s life difficult to live.

The evolution of the lower limb prosthesis over the recent decades has progressed from purely mechanical systems to systems that include processor controlled programmable device. The requirement is to develop an intelligent prosthetic device which can adapt the style of the patient or person who is wearing them. The options available are both locally manufactured and imported ones. ALIMCO Kanpur and Bhagwan Mahaveer Viklang Sahayatha Samiti (BMVSS) Jaipur (Jaipur foot) are the major players who manufacture the mechanical prosthetic devices for the masses (Fig. 1.1). The available prosthetic products are merely a poor replacement of amputated limb as they are not able to perform coordinated and complex movements required in a knee joint. The sophisticated import options are available but they are very costly to afford even by affluent persons and are thus, rarely seen. One Electronic Knee from OttoBock costs around Rs. 18-20 lakhs. Therefore this study has focussed to generate an optimal control mechanism for a low cost artificial prosthetic device. Advent of numerous sensors, microcontrollers, accurate feedback controls and integration of technology, allow engineers and doctors to incorporate required features to artificial limbs to make them comfortable for users. In the present era,
orthotic and prosthetic devices can no longer be seen as separate, lifeless mechanisms but they need to be intimate extensions of the human body—structurally, neurologically, and dynamically. Therefore there is an urgent requirement for an Above-Knee Prosthetic (AKP) device which can be programmed and controlled to adapt according to amputees of any age or physical condition.

![Fig. 1.1: a) ALMICO Kanpur AKP, b) BMVSS Jaipur AKP](image)

Development of orthotic and prosthetic devices has been highly influenced by the growth of science and technology. Historical records prove that the first instance of amputations and prosthetic replacement appears in Vedas during 3,500 and 1,800 B.C. First known written account about an amputee describes warrior Queen Vispali who returned to battle after being fitted with an iron leg. In 220 BC, Roman General Marcus Sergius lost his right hand in his second campaign. He was fitted with an iron hand (Fig. 1.2a) and went on to successfully lead many expeditions. In 1564, French army surgeon Ambroise Pare invented a trans-femoral prosthesis that could be fixed into positions for standing, kneeling, and horseback riding (Fig 1.2b). In 1800, James Pott of London designed a wooden prosthesis (also called the clapper leg because of the sound, when used, due to wooden foot stops), with steel joints and catgut tendons for the Marquis of Anglesey (Fig. 1.2c). In 1856, American A. Marks added to it knee, ankle, and toe movement with articulation control\(^1\).
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With the development in engineering skills, the structure of prosthetic devices changed in terms of material, functionality, intelligence and adaptability to amputees. However, the current science and technology generated concept of system aspect (sensors, control, actuation, interface, communication etc) has been integrated into prosthetic device, patient and environment. Existing methodologies of feedback control have been refined significantly in order to allow knee electronic control to obtain a real time dynamic state specific knowledge. The contribution of complex feedback sensors and control system, therefore, concurs to device’s design equipped with high degree of adaptability and reliability. Figure 1.3 shows a schematic of such an artificial knee which is studded with different kind of sensors responsible for sending dynamic state of the device to controller, which is calculating control parameters through software algorithms and generating a real time control.

Fig. 1.3: Sensors fitted on Electronic Knee
Biomechanics and Bioengineering help in designing the prosthetic devices. The main problem with the country manufactured prosthetic devices is that their development is not based on any scientific input parameter of human movement. Any attempt to establish the optimal control mechanism of prosthesis requires the observation of basic walk progression. The scientific analysis of human movement for estimation of control parameter is called as Gait Analysis. More intelligent device with respect to efficiency, accuracy and comfort can be produced by using gait parameters. Many aspects of human anatomy, behavior and other physiological traits of the individual need to be considered to design a user friendly prosthesis. Gait Analysis can also be used to evaluate various feedback techniques devoted to achieve real natural gait, less stress and minimal patient interaction.

Another important aspect where the indigenous prosthetic devices lack in performance is the fitment of these devices to the patient. For optimum performance of the above knee prosthetic, there are various types of socket design, material choice and fabrication techniques. A very common case of performance is deterioration of a good prosthetic device fitted with an improper socket. Non standard practices and procedures in these areas limit performance of many good prosthetics. There is a need to have scientific procedure based on gait analysis for prosthetic fitment and training of patient. The rehabilitation and training of an amputee using an assistive device is a challenging task and very important as the effect on the mind due to the loss is much more than on the body.

1.1 Prosthetic Biomechanics

Prosthetic biomechanics is the demonstration of the practicality of biomechanics, when applied for orthopedic assessment and prosthetics design. Broadly, it is the application of mechanical principles to the human limb movements. This includes bioengineering, the research and analysis of the mechanics of living organisms and the application of engineering principles to and from biological systems. Biomechanics has been defined as the study of the movement of living things using the science of mechanics. Mechanics is a branch of physics that is concerned with the description of motion and how forces create motion. Forces acting on living things can create motion, be it a healthy stimulus for growth and development, or overload tissue, causing injury. Biomechanics provides conceptual and mathematical tools that are necessary for
understanding how living things move and how it might improve movement or make movement safer. Biomechanics has numerous application areas in the prosthetic design. It provides the background science to identify control parameters which can be sensed for making device adaptive and programmable. Concept of anthropomorphicity is a key tool in planning the design of an artificial limb or its components.

Biomechanics of how an amputee walks, has both clinical and nonclinical applications. The finding may help to relate the user requirement and specification of a prosthetic to be fixed. With biomechanics inputs, developed prosthetic designs permit amputees of all levels and ages to ascertain the prosthetic usage limitations. For improved amputee care, prosthetist and physical therapist must maintain a certain level of knowledge in this area like prosthetic socket fabrication, component selection and the design of an appropriate training program that will assist the amputees in attaining their goals.

1.2 Gait Analysis

In very simple terms, Gait analysis is the way in which an individual walks. Walk of every individual is like finger print i.e. it characterizes the person. Gait is the result of muscle action exerting forces on the skeletal limb segments in a coordinated way to change motion, and hence locomotion, as we interact with our external environment. The systematic measurement, description, and assessment of biomechanical quantities that characterize human walking task is termed as gait analysis. There are various definitions of gait analysis; In terms of Biomechanics it is a cyclic progression of centre of gravity which involves weight acceptance & forward swing. Walking is defined as ‘progress by lifting and settling down one feet at a time in turn, never having both feet off the ground at once’. Gait means ‘progressive movement of the entire body from one place to another by self propulsion’. The term "normal gait" is used to present those parameters that have been generalized across sex, age, genetic predisposition and anthropometric variables. Clinical gait analysis allows the measurement and assessment of walking biomechanics, which facilitates the identification of abnormal characteristics and recommendation of treatment alternatives.
Gait Analysis is used for quantitative measurement of human walking, stair ascending-descending, obstacle avoidance etc. The study encompasses quantification, i.e. introduction and analysis of measurable parameters of gait, as well as interpretation, i.e. drawing various conclusions about the subject (health, age, size, weight, speed, etc.) from its gait. A standard physical examination cannot provide a complete description of the complex phenomenon of abnormal human gait. But gait analysis can give qualitative as well as quantitative values of gait parameters\textsuperscript{16}. Significant technical and intellectual progress has been made in the area of gait analysis over the past few decades, especially because of advances in computing speed which in turn has aided the development of more advanced movement-recording systems that require less data processing time\textsuperscript{17}. Improved computing speed inspired increasingly complex and innovative gait data analysis techniques. Gait analysis has evolved to be an indispensable tool in the design, development and control of modern day prosthesis. It gives the quantitative analysis report which acts as feedback for correct design and development. The main advantages of using statistical techniques is that they provide insight into the gait models being used and the effects of the various independent variables on the dependent variables can be studied directly\textsuperscript{18}. In addition, gait analysis also plays a very significant role in the training and rehabilitation of the amputee using the prosthesis.

1.2.1 Gait Terminology

Gait is a periodic activity and the terminology used to understand the fundamentals of gait analysis and identify gait events has been discussed in the subsections below:

1.2.1.1 Gait Cycle

The gait cycle is used to describe the complex activity of walking, or our gait pattern. This cycle describes the motions from initial placement of the supporting heel on the ground to when the same heel contacts the ground for a second time. Human gait is a quasi-periodic activity with the left and right limbs out of phase. Control of the whole body and specifically the lower limbs, is often described in terms of the magnitude of parameters at key events and during key phases that occur during the gait cycle\textsuperscript{16}.
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**Mid Stance:** It is the period of the gait cycle between opposite toe off and heel rise. The first half of single support is termed mid stance (10-30% GC) and is involved with progression of the body center of mass over the support foot. This trend continues through terminal stance (30-50% GC). This phase includes heel rise of the support foot and terminates with contra-lateral foot contact.

**Pre Swing:** It is the final stance element. Pre-swing (50-60% GC) is related functionally more to the swing phase that follows than to the preceding stance phase events. Pre-swing begins with terminal double support and ends with toe-off of the ipsi-lateral limb.

**Initial Swing:** The initial swing phase from 60 to 73% of the gait cycle is defined from toe-off to when the swing limb foot is opposite the stance limb. It separates pre-swing from initial swing and it is the point at which the stance phases ends and the swing phase beings. The name terminal contact has been proposed for this event, since in pathological gait, the toe may not be the last part of the foot to leave the ground.

**Mid Swing:** It is the time when the swinging leg passes the stance phase leg and the two feet are side by side (73-87% GC). It is also termed as ‘feet adjacent’ because this identification separates initial swing from mid swing. Excessive planter flexion in mid swing drops the foot below horizontal. The immediate effect is toe drag on the floor and inhibition of limb advancement.

**Terminal swing:** The division between the period of mid swing and terminal swing is marked by the tibia of the swinging leg becoming vertical, which occurs at 87-100% GC of the gait cycle in the subject under observation. Terminal swing is also known as ‘reach’. Generally, a toe drag that is present in mid swing is corrected by the terminal swing lift of the foot. Hence, persistent toe drag indicates a mixture of excessive ankle planter flexion and inadequate knee extension.

The swing phase achieves foot clearance and advancing of the trailing limb.
Figure 1.6 shows the phases, sub-phases and events of a single gait cycle for a detailed gait analysis. It should be noted that all events must be reproducible i.e. the events occur in all participants in the study.

Fig. 1.5: Positions of legs during a single gait cycle of the right leg (gray color)

Fig. 1.6: Schematic representation of phases and sub-phases of a normal Gait Cycle
1.2.1.3 Gait timings:

The timing of gait cycle is divided into various parts based on the gait phases discussed above. In each gait cycle, there are two periods of double support and two periods of single support. The stance and swing phase duration are typically 60% and 40% of gait cycle respectively but this duration varies with the speed of walking. The swing phase becomes proportionately longer and the stance phase and double support phases shorter, as the speed increases.

**Stride length:** A stride is the equivalent of a GC (Fig. 1.7). The duration of a stride is the interval between sequential initial floor contacts by the same limb. Stride length again consists of two step lengths.

**Step Length:** It is linear distance in the plane of progression between corresponding successive contact points of opposite feet (e.g., distance measured from heel strike of one foot to heel strike of the other foot). Stride length, measured between successive positions of the left foot, must always be the same as the stride length measured between successive positions of the right foot, unless the subject is walking around a curve.

**Stride width:** It is the side-to-side distance between the line of two feet, also known as the walking base or base of support. It is usually measured at the midpoint of the back of the heel but sometimes the measurement is done from below the center of the ankle joints. The preferred units for stride length and step are meters and for stride width, millimeters.

![Diagram of gait cycle](image-url)

Fig. 1.7: The stride length and step length of an individual
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Cadence: Cadence is the number of steps per unit time, the usual units being steps per minute. It is scientifically acceptable to measure cadence in steps per second, but there is currently a trend to replace cadence entirely by a quantity which is inversely related to it—the cycle time, also known as ‘stride time’ in seconds:

\[
\text{Cycle time (s)} = \frac{120}{\text{cadence in steps/min}}
\]

Speed of walking: It is the distance covered by the whole body in a given time. It should be measured in meters per second. The cadence, in steps per minute, corresponds to half-strides per 60 seconds or full strides per 120 seconds. The speed thus can be calculated from cadence and stride length using the formula:

\[
\text{Speed (m/s)} = \frac{\text{stride length (m)} \times \text{cadence (steps/min)}}{120}
\]

Cycle Time: If cycle time is used in place of cadence, the calculation becomes much more straightforward:

\[
\text{Speed (m/s)} = \frac{\text{stride length (m)}}{\text{cycle time (s)}}
\]

1.3 Techniques for Gait Measurement

Gait analysis is used for two very different purposes: to aid directly in the treatment of individual patients and to improve our understanding of gait. Later on it is subdivided into fundamental studies of walking and clinical research. There is no single method of analysis suitable for such a wide range of uses. A number of different methodologies and techniques have been adopted. Gait analysis involves the measurement of the movement of the body in space (kinematics) and the forces involved in producing these movements (kinetics). It is the assessment of human walking parameters which affect the normal gait. It is started with the clinicians and physicians interested to find out the abnormalities for disease diagnosis and their treatment. Gait analysis helps to distinguish between normal and pathological gait, estimate the course of an orthopedic problem and assess the need for prosthetic and orthotic devices for the upper and lower limbs. Decades ago, Gait analysts were the experts who over the year became judges of human walk by merely observing person’s gait. For qualitative purpose, this observational gait analysis is a workable solution but as the walking complexity increases with organic pathology,
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objective analysis becomes necessary. Observational gait analysis suffers from four serious limitations:

✓ Due to transition, gives no permanent record
✓ The eye cannot observe high speed events
✓ It is only possible to observe movements, not forces
✓ It depends entirely on the skill of the individual observer

A typical gait analysis procedure involves recording a number of biomechanical variables, often using a number of different measurement techniques. With the advent of measurement and analysis science, the number of gait parameters to be recorded and analysed are increasing and thus making gait analysis a very complex procedure. Therefore, for gait analysis, synchronization of various measurements is essential. Biomechanical analysis of human movement requires information about motion (kinematics), human inertia parameters and internal and external forces (kinetics). It is generally agreed that a detailed laboratory-based clinical gait analysis test can be achieved using:

(a) Motion measurement system (motion analysis)
   i. Contact based (Electrogoniometers)
   ii. Non Contact based (Camera Motion Analysis system)

(b) Force platform (measuring the forces exerted on the ground by the foot)

(c) Physiological analysis by Electromyography (EMG) System

The various techniques which can be useful for measurements in gait analysis are represented in Fig. 1.8. The measuring and recording instruments for kinetic analysis are force plate, pressure mats and foot pressure insoles used for dynamic gait assessment. Kinematic analysis is done by attaching sensors to body or through motion analysis system. For physiological assessment EMG and energy expenditure parameters are acquired and analysed. It is sometime necessary that the gait measurements are done in laboratory or outside the laboratory. Therefore the instrumentation scheme must support both the environments.
1.3.1 Motion Analysis System (Kinematics)

Motion analysis or Kinematics refers to the description of patterns of performing limb or body motion independently. Kinematics is the study of the “output” or motion of the activity, independent of the “driving” or “input” forces that change the properties of the motion. Linear and angular displacements, velocities, accelerations, center of rotation for joints, and joint angles are all examples of kinematics. Kinematic information can be collected using direct (contact based) measurement techniques (i.e. goniometers, accelerometers) and with indirect (non contact based) measurement using imaging techniques (i.e. cinematography, high-speed video, stroboscopy)[22, 23, 24].

1.3.1.1 Direct Motion Measurement Systems

There are a number of systems which measures the motion of body or leg using some form of direct connection to the subject. This technique of measurement involves simple device and non complex procedures, but it has a serious inherent limitation that as the sensor is attached to joint or body part it results in non natural gait of subject. Various measurement devices are explained in the subsection below[25, 26, 27]. The sensors describe below give an estimate to measure gait.
parameters and these spatiotemporal parameters observed with respect to walking speed can use to detect any abnormality.\textsuperscript{28}

1.3.1.1 Goniometers and Electrogoniometers

These devices are used for making continuous measurement of the angle of a joint. Goniometers (Fig. 1.9a) vary from the very simple mechanical linkages which are generally used for measuring an angle across one joint in one plane in static positions, to the more sophisticated electronic goniometers (electrogoniometers) (Fig. 1.9b). Electrogoniometers are used for gait analysis as they are essentially electric potentiometers or transducers that produce an output voltage proportional to the angular change between the two attachment surfaces. The electrogoniometer is not attached to an external landmark in proximity to the joint centre, but instead has attachments to the two segments spanning the joint, so they literally measure the angle between the sensors as they are attached to the segments. They operate on the assumption that the attachment surfaces move with (track) the midline of the limb segment on to which they are attached, and thereby, measure the actual angular change at the joint.

Electrogoniometers can be used to measure angles in a single plane or for bi-planar movements like biaxial devices can simultaneously measure sagittal and frontal plane motions.\textsuperscript{9} Electrogoniometers are relatively inexpensive, easy to use, portable and do not require attachment to joint centers and can be used in the field situation to provide joint angle information in real time.

![Fig. 1.9: (a) Goniometer, (b) Electrogoniometers](image-url)
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1.3.1.1.2 Accelerometers

Accelerometers are the transducers working on the principle of inertia to measure accelerations in one to three dimensions. There are three common types of accelerometers:

I. Piezoelectric: Exploits the piezoelectric effect whereby a naturally occurring quartz crystal is used to produce an electric charge between two terminals.

II. Piezo-resistive: Operates by measuring the change in resistance of a fine wire when it is mechanically deformed by a proof mass.

III. Variable capacitive: Change in capacitance is proportional to acceleration.

Velocities can be derived through integration of the acceleration-time data and a second integration will provide the displacement as a function of time. While carrying out these integrations, initial conditions have to be provided which can be difficult to determine in some movement tasks. Nonetheless, the acceleration output from accelerometers is instantaneous and useful when basic acceleration information of body segments is of primary interest in an investigation, for real-time biofeedback and for data collection in the field. It is perhaps surprising, especially in clinical biomechanics, that more attention has not been given to accelerometry since these are accelerations which are the drivers of motion in the human body, and all the velocities, displacements and changes in velocities and positions of segments are the outputs derived as a result of accelerations. Figure 1.10 shows a Biometrics tri-axial accelerometer.

![Fig. 1.10: Tri-axial accelerometer](image)

1.3.1.1.3 Footswitches

Footswitches are the simplest, convenient and inexpensive devices used to detect/measure the gait events and temporal parameter data. They are adaptable to any situation, including field
measurements over large distances and treadmill walking. Footswitches, if placed under both feet, record step-by-step temporal information. This basic, yet essential, gait information is recorded in many gait studies and has been the only data collected in some highly complex research into long-term gait control. There are two basic types of compression closing and force sensitive resistor (FSR) switches, usually configured as thin insoles, which can be placed between the foot and shoe or taped to the bottom of a bare foot. FSR switches (Fig. 1.11) consist of two thin layers of flexible plastic, with printed circuits on the inner surfaces, separated by a thin layer of double-sided adhesive. Footswitches measure timing of foot placement information and can detect the gait events and measure the temporal parameters of gait cycle time, stance time, swing time, single support time and double-stance times. FSR systems are available as insoles or as discrete switches that can be placed in user-specified areas beneath the foot. Footswitches typically have contact areas in some part or the entire heel, first and fifth metatarsal and great toe areas. The advantage of discrete switches is that different size insoles are not required to fit a large range of foot sizes. Footswitches provide important gait timing data that are difficult to obtain automatically in any other way, especially over a number of steps (e.g., outside or treadmill walking). There are a number of different types of footswitches available both as commercial products or they can be built in-house. They can also be bought or built at low cost.

Fig. 1.11: Various types of Foot switches & FSR available
1.3.1.1.4 Gyroscopes
Orientation of the body segments in space is measured with the help of Gyroscope and angular velocity and acceleration of any moving subject is recorded by attaching a transducer called ‘rate-gyros’. Angular velocity-time plots taken from the lower limbs exhibit unique characteristics or patterns which can be processed to derive various spatial-temporal events and parameters of gait such as velocity, step/stride lengths, stance/swing times. This type of data-recording involving gait is particularly suitable for situations demanding outdoor recording and may also be suitable for the clinic or rehabilitation setting. The advantages of gyroscopes include the direct measurement of rotational motion that is not influenced by gravity and small size. Disadvantages include increasing error of several degrees per second caused by gyroscope offset and noise.

1.3.1.2 Indirect (non-contact base) Measurement Systems: Camera Motion Analysis
The very primitive motion analysis system is the human eyes that record and analyze the normal vs. abnormal gait. Pioneering work of Marey and Muybridge (1870), gait analysis was done with video cameras for almost 100 years. The patient videos were carefully viewed and observed many number of times as they walked up and down. Visual recording of patient trials made the gait analysis easy to locate the details, and also helped in reducing the numbers of patient trials. The multiple cameras are placed on both sides and in front & back for video recording. The minimum number of camera systems required to view a patient is two, but to examine both legs at the same time, and to minimize problems with markers being obscured, the best results are obtained using 5 or 6 cameras. Previously the tape was analysed manually, looking for a number of gait abnormalities. Later on various software tools were adopted to perform the laborious task. The videotape-based systems are generally less expensive, but are less convenient to use, and may not be as accurate as the image obtained is 2D (with single camera). For minimizing the limitation various transformations have been carried out in terms of image quality and marker technology (active and passive markers). In a typical clinical gait laboratory camera motion analysis is done with minimal clothing as clothes hinder the marker placement and their view through cameras.

For more accurate and precise measurement of human motion in 3D space, 3D motion image construction and analysis is done. The 2D motion analysis measures all the basic temporal spatial
measures like the timing and occurrence of the “tibia vertical” and “foot clearance”. 3D motion analysis offers all this and much more. In fact, 3D motion analysis is as much easier these days as 2D motion analysis, though much more expensive. Modern motion analysis systems generally capture 3D motion data in an automated fashion and in real time. For normal applications 2D motion capture is still preferred considering its low cost. There are four main types of motion analysis equipment, referred to as:

- **Video digitizing systems** (e.g., Peak): Use manual digitizing on video pictures, frame by frame, or automated digitizing/tracking of reflective markers post-video-capture. Video is the only option for 2D analysis (no commercial 2D non-video-based systems are available) and video is the only option in situations when attaching markers to the study’s participants is not possible.

- **Video-based reflective/passive marker systems** (e.g., VICON, Motion Analysis, Elite, Qualysis, Peak): Use reflective markers (passive markers) attached to the participant. Cameras pick up the reflections from the markers. These systems automatically capture marker positions and most systems present 3D position-time data of markers in real time or near real time.

- **Optoelectronic or active marker systems** (e.g., Optotrak, CODA): The markers themselves are infrared-emitting (active markers) and individually identifiable. These systems automatically capture 3D position-time data of markers in real time.

- **Magnetic tracking systems** (e.g., Ascension, Polhemus): Unlike the other three optical-based systems, magnetic fields are used in this technique. Instead of markers they have sensors, each of which gives data in six degrees of freedom (three coordinates and three angles) in real time.

The typical layout of the camera motion gait analysis laboratory is shown in Fig. 1.12. There are multiple cameras mounted on a tripod or fixed in wall which capture the movement of the subject. All the cameras are networked to a computer system through suitable data acquisition interface which records the trials. The data acquisition unit synchronizes the other gait input parameters from force plate and EMG system. The computer with gait analysis software, analyses the stored data offline.
1.3.2 Kinetics (Force)

The propulsion of body from source to destination requires internal (muscle activity, ligaments, friction in muscles and joints) and external (from the ground, active bodies, passive bodies) forces. The measurement of these external forces that body gets from the outside environment is done with force platforms, pressure mats, shoe insole sensors etc. The measurement of internal forces is done with physiological parameters measurement techniques like EMG. Measuring external forces along with synchronized kinematics (motion) data is useful in calculations of joint forces and joint moments.
1.3.2.1 Force Platforms

Force platforms or force plate systems (Fig 1.13a) are used to measure the ground reaction forces generated by a body standing on or moving across them (Fig 1.13b), to quantify balance, gait and other parameters of biomechanics. They are usually embedded in a walkway and record foot-ground reaction force and moment time histories. Ground reaction forces (GRF) are the reaction forces as a result of contact between the foot and the ground, and these form an integral part of human movement analysis. There are two types of force platforms commercially available:

- Piezo-electric transducers (e.g., Kistler)
- Strain-gauge transducers (e.g., AMTI, Bertec)

Force platforms are different from pressure measuring systems (pressure mats) which quantify centre of pressure but are not able to measure directly the applied force vector. Advantage with force plate is that along with quantifying the foot pressure patterns over the time they also measure the horizontal or shear components of the applied forces. Kinetic information along with the kinematic data can allow the determination of torque, work and power at each joint using the method called inverse dynamics\textsuperscript{291}.

1.3.2.2 Pressure Mats and Foot Pressure Insoles

The measurement of the pressure under the foot is a specialized form of gait analysis, that allows the measurement and analysis of the distribution of one dimensional pressure (vertical for pressure mats and normal to the sensor for pressure insoles) on the plantar surface of the foot. The mats (Fig. 1.14a) are most beneficial in detecting pressure profile discrepancies in children as well as patients (diabetic neuropathy) with deformed feet. This finding of these measurements...
is useful in another branch of biomechanics called Foot biomechanics. Foot pressure sensing can quickly determine the areas beneath the foot that may be subject to tissue breakdown (Fig. 1.14b).

Pressure mats are of a similar size and shape to a force platform and they are also placed within a walkway. The patient walks barefoot across the mat. The advantage of the pressure mat is that nothing needs to be attached to the individual but the disadvantage is that only barefoot walking gives reliable pressures felt by the foot (if shoes are worn, the pressure between the ground and the underneath of the shoe is measured).

If the pressure on the underside of the foot while wearing a shoe is required or the effects of various orthosis are to be evaluated, then a pressure-sensing insole (Fig. 1.14 c) must be used. Apart from in-shoe measurement, insoles have the added advantage of being able to measure multiple consecutive gait cycles on one or both feet. The insole must be protected from possible damage and the clinician must insure that the floor/insole interface does not create a slipping hazard for the wearer. There are two main manufacturers of pressure insoles, Novel (Pedar) and Tekscan (F-Scan), but they are quite different products. The Pedar system uses capacitive transducers and they last many years. The F-Scan system uses FSR transducers and each insole lasts for only a few minutes of continuous walking (i.e., insoles are consumables).
1.3.3 Physiological Signal: Electromyography (EMG)

Technique for evaluating and recording the electrical activity produced by skeletal muscles is called Electromyography (EMG). EMG signal detects the electrical potential generated by muscle cells when these cells are electrically or neurologically activated and thus gives the intensity of muscle activity. Broadly, the quality and quantity of acquired signal depends on the type of electrode used i.e. surface (active & passive) or needle electrodes (Fig. 1.15 a, b, c respectively). Generally surface electrodes are used in biomechanics as they are non-invasive and easy to use. The main disadvantage of surface electrodes is that deep muscles cannot be monitored because of crosstalk (electrical activity) from other muscles that lie between the deep muscles and the surface electrode.

![Active electrode](a), Passive electrode](b), Needle electrodes](c)

Fig. 1.15: a) Active electrode, b) Passive electrode, c) Needle electrodes

EMG is used to detect medical abnormalities, activation level, or to analyze the biomechanics of human or animal movement. The analysis is categorized as: clinical (diagnostic EMG) and kinesiological. Diagnostic EMG, typically done by physiatrists and neurologists, are studies of the characteristics of the motor unit action potential for duration and amplitude. These are typically done to help diagnose neuromuscular pathology. They also evaluate the spontaneous discharges of relaxed muscles and are able to isolate single motor unit activity. Kinesiological EMG is the type most found in the literature regarding movement analysis. This type of EMG studies the relationship of muscular function to movement of the body segments and evaluates timing of muscle activity with regard to the movements. The problems with EMG signal analysis is that at its best it gives only a semi quantitative technique and it is difficult to obtain satisfactory recording from a walking subject. This happens partly due to electronic characteristic of measuring system and partly due to lack of skill of the operator in selecting the recording sites and in attaching electrodes. Raw EMG signal is collected and analysed for the
onset, duration, and amplitude of muscle activity of the leg muscles during a gait cycle. For multiple gait trials normalization and averaging is done. In time domain RMS amplitude curve provides the quantitative value for muscle force generation. In frequency domain, Fourier analysis gives power spectrum of signal. Lots of research is going on in the EMG controlled prosthetic devices\textsuperscript{32,33}.

1.4 Technological Status of Prosthetic Knee

An artificial limb is a type of prosthesis that replaces a missing extremity, such as an arm or a leg. There are various reasons which we discussed in the beginning and that are responsible for increasing alarmingly the number of affected individuals. Innovation and invention in prosthetic technology is a continuous journey from Stone Age to present day for making the amputee life comfortable. Natural Walking is a complex process to understand and to replicate artificially. Transfemoral amputees have a very difficult time regaining normal movement. This is due to the complexities in movement associated with the knee. Lower limb amputation affects the ambulatory capabilities of individual and therefore, special emphasis has been laid by scientists and technologists to develop significant advancements in Above Knee (AK) limbs. New plastics and other materials, such as carbon fiber, have allowed AK to be stronger and lighter, limiting the amount of extra energy necessary to operate the limb. This is especially important for transfemoral amputees as walking with prosthetic knee require 80\% more energy than with natural legs \textsuperscript{34}.

In addition to new materials, the use of electronics has become very common in artificial knee. There are prosthetic knees which can be controlled by converting muscle movements to electrical signals, called myo-electric knees. Microcontrollers and high end processors are also used extensively for controlling the process in different environments. Electronics circuitry is shrinking day by day and since new devices consume less power, the prosthetic may be operated for many days in continuation before recharging. Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) are often used to assist in the design and manufacturing of artificial limbs.
Socket is important component of AK as it holds the residual stump of the patient and provides linkage between limb and prosthetic. Most modern artificial limbs are attached to the stump of the amputee by belts and cuffs or by suction. The socket is custom made to create a better fit between the leg and the artificial limb, which helps to reduce wear on the stump. Newer methods include laser guided measuring which can be inputted directly to a computer allowing for a more sophisticated design\textsuperscript{35, 36}.

Newer and more improved designs employ hydraulics, carbon fiber, mechanical linkages, motors, computer microprocessors, and innovative combinations of these technologies to give more control to the user. This research and development is continuing. As a result, there are many different designs of prosthetic knees available off-the-shelf ranging from simple hinges to sophisticated electronic devices.

1.4.1 Types of knee technologies available

They comprise six types:

1.4.1.1 Manual Locking: This is the most stable knee available in the market. As the patient walks, the knee does not bend at all. The knee only bends with a manual release for sitting. Locking knees have a manual lock, which prevents any flexion throughout the gait cycle. They offer the greatest stability but produce an awkward gait, and are appropriate for older adults who are unsteady on their feet or have poor muscle tone in the residual limb.

1.4.1.2 Constant Friction: This type of knee allows for single speed walking on level surfaces. The basic single-axis is constant sliding friction knee unit, which is light-weight, durable, and less expensive, is frequently used on temporary basis and for children’s prostheses, which are usually replaced annually. Although the basic unit allows only one optimal walking speed, some versions have friction mechanisms and weight-activated brakes. The brake is often used with inexperienced walkers to help protect them from falling.

1.4.1.3 Stance Control: This knee is very stable and is usually prescribed as patient’s first prosthesis. When weight is placed on the prosthesis, the knee does not bend until weight is removed, allowing for clearance during walking.

1.4.1.4 Polycentric: Polycentric knees are naturally stable, are recommended for older patients and can be used with long and short residual limbs. Polycentric knees are a good choice for
active users who desire gait stability without the expense of a computerized knee unit. Polycentric knees, sometimes called “four bar” knees, are designed to be stable in early stance and to flex easily during pre-swing. The polycentric knee varies its center of rotation during ambulation so that the weight line lies anterior to the instant axis of knee rotation for a period longer than that with a single-axis unit\(^{38,39}\). Polycentric knees add weight to the prosthesis and have more moving parts that need to be serviced regularly.

1.4.1.5 **Fluid-controlled:** This knee is prescribed for patients with the ability to walk with varying speeds. Fluid-controlled knees are either pneumatic (air) or hydraulic (oil). They automatically increase or decrease swing phase resistance as users vary their walking speed. More active clients benefit from a single-axis or polycentric knee that incorporates a fluid-controlled unit. As the person walks faster, the piston inside the unit limits the flow of fluid, and thus, control of knee flexion. When the user walks slowly, the air or fluid flows easily, enabling the knee to move more slowly. In extremely cold weather, a fluid-controlled knee that uses silicone is a good choice.

1.4.1.6 **Microprocessor controlled:** The newest of the knee designs, this state-of-the-art knee has an onboard computer which provides an extremely efficient and natural gait. Microprocessor control of computerized knees is based on biomechanical studies. Most units respond to information from sensors that detect the amount of force borne on the foot, the angle of the knee, and the speed of shank swing. The internal processor automatically adjusts the response of the knee to the walking surface encountered by the user. The prosthetist uses a PC to adjust the knee to the individual’s gait pattern. The knees are powered by a lithium-ion battery that provides 25 to 30 hours of use before need of recharging.

1.4.2 **Products Available**

There are wide varieties of products available in market nationally and internationally varying greatly in price. Unfortunately in India, very few indigenous AK prosthetic are available. Two organizations-ALIMCO Kanpur and BMVSS Jaipur are involved in manufacturing the products which are merely a cosmetic replacement as they have very limited functional capabilities. The cost of the product varies from Rs. 15000/- to Rs. 20000/- for a mechanical knee and there is no electronic knee being manufactured locally. The major problem with the rehabilitation devices
available is that they are not incorporating gait analysis for parameter evaluation and design inputs.

International companies like Otto Bock, Endolite and few others are the major players. Otto Bock have AK named as C-Leg® microprocessor based knees (Fig. 1.16a) which are designed to deliver the best in stability and reliability\textsuperscript{[40]}. It is suitable for transfemoral amputees who are involved in activities that require a high level of stance stability or when it is required to walk on uneven terrain and frequently descend stairs or negotiate slopes. C-Leg wearers can choose between two modes that are programmed by their practitioners. The first mode would be optimized for the patient's daily activities while the second mode would be programmed for activities in which the amputee participates. C-Leg offers three different modes of operation and changing between modes can be done by wireless remote control. It uses lithium ion batteries with 40-45 hours of operation. The cost of C-Leg is around Rs. 18-20 Lakhs which is highest in this category.

The other comparable product is from M/s Endolite named as Smart Adaptive (Fig. 1.16b). The cost of adaptive knee is cheaper than C-Leg, it is between Rs. 8-15 Lakhs. The Smart Adaptive uses hybrid device i.e. hydraulic unit for stance phase control and pneumatic unit for swing phase control. It also has a smart memory card-to retain amputee specific data which can be downloaded on to an adaptive prosthesis at a later date. The knee is programmed with a programmer. The microcontroller calculates and provides variable pneumatic resistance settings and boundary thresholds with their appropriate spread to be stored for the swing control. This covers slow to fast swing speeds. Once the Smart Adaptive is programmed, it can automatically detect walking speed and can control resistance settings during amputees use it.

Another knee is available as Rheo Knee (Fig. 1.16c). This development was done by the Massachusetts Institute of Technology (MIT). The Rheo knee's microprocessor adjusts resistance 1,000 times per second during stance, maintaining knee stability on uneven terrain. By identifying a variety of walking speeds and then updating flexion and extension resistance accordingly, the knee improves gait symmetry and efficiency. The Rheo knee can be used with any foot component. The PDA user interface is easily adjustable and supports multi-functional use. Depending on activity, the knee's lithium battery holds a charge for 24 to 48 hours and can be charged in 2 to 4 hours.
It is clear from the above discussion that there is no indigenous electronic knee available and the available imported options are exorbitantly costly that even affluent individuals find difficult to afford. In the past, and still to a large extent in the present, orthotics and prosthetics focused primarily on using the residual limb and musculature for attachment, mechanical leverage and activation. Some of the more advanced commercially available devices use surface-attached myoelectric sensors, powerful self-contained microprocessors and computer-controlled actuators and motors to emulate natural biological functions. However, further advances toward the goal of a fully integrated “thought-controlled” device will require interfaces directly with nerves inside the body for direct neural control—a more biologically driven and medically assisted direction.

1.5 Research Aims and Objectives

Achieving natural walk with an artificial prosthetic device is still a challenging task for scientists and engineers. It is evident now that the products available are not up to the mark as they don’t involve science into it. Gait analysis and Prosthetic Biomechanics can give the design inputs and control parameters to have a state-of-the-art artificial above knee prosthetic (AKP). Biomechanics and Gait analysis have been used in the past for clinical representations and diagnosis of anatomical abnormalities. In addition there is little information available for Indian
population gait data and thus very few research articles describe its impact in AKP design and control. Dynamic feedback and real-time control of AKP is one of the strategic solutions to the problem. Thus there is a need to derive a feedback mechanism based on study of gait parameters for optimal control methodology. Research so far has been concentrated on the design of an above knee prosthesis which provides all the features desired by an amputee for the best possible near normal walk. An important factor that has been often ignored is the cost-effectiveness of the designed product. Emergent need is the development of an intelligent, user adaptive, versatile prosthetic device at a cost affordable to common man who is an easy victim to man-made calamities. Any loss of a lower limb of a working man usually results in the loss of the family's livelihood and poverty becomes inevitable. Indigenously developed artificial lower limbs are satisfactory for walking but rarely adequate for hard manual work. It is the common man who is most affected by an amputation and not the one who can afford multimillion, high end prosthesis available in the market. The challenges on the development of a cost effective above knee prosthesis for trans-femoral amputees can be overcome by the use of easily available sensors attached to it and by an optimal control strategy for the controller. The research work here focuses on the design of user adaptive, intelligent, programmable prosthetic device at an affordable cost for common man.

The novelty of the proposed design is that it uses indigenous sets of gait data and parameters as design inputs and provides an integrated approach in the control of the prosthesis. Sensors like FSRs, goniometer and accelerometer feed real time data to the controller which decides the speed of the walk comparing the control ranges generated during training of the device on patient. Approach to control the device with surface EMG (SEMG) signals from the normal limb activity as control parameter, adds to the uniqueness of the control strategy design. Detailed analysis on the control strategy is available in the chapters to follow. The use of indigenous gait data and in-house developed sensor results in an economical prosthetic device which is costing a fraction of the imported device.

The scene of quantification of a developed prosthesis is still on the darker side. A better approach for the quantification of the prosthetic device is needed rather than reliance on mere visual observation and questionnaire to the patient. An instrumented gait analysis serves this purpose, which has been focussed in this study.
From the above detailed discussions, it can be easily derived that there is a wide scope of research to develop adaptive, intelligent and cost effective prosthetic devices to suit common man whose lower limb has been amputated resulting in huge suffering to the family through crippling to the family finances.

1.5.1 Objectives

The major objectives of the work are:

✓ Development of a Gait Measurement system for easy and cost effective determination of spatio temporal parameters of human gait and prosthetic quantification.

✓ Collection of gait data of normal healthy individuals and identification of suitable gait parameters which can be correlated for use in development of prosthesis.

✓ Improvement in sensors mechanism to provide dynamic and real time control of an artificial prosthetic device. Based on the programmability of the device, sufficient intelligence to be embedded into the system to make it truly adaptive.

✓ Deriving a control strategy utilizing the data from sensors fitted on the designed prosthesis, behavior of the gait parameters during walk vis-a-vis user comfort level.

✓ Evaluation of developed AK prototype on the basis of gait parameters for accurate control, reducing the control complexity and enhancing user comfort. Assessment of dynamic feedback topology based on physiological signal (EMG) for controlling artificial limb.

1.6 Overview of the Thesis

To successfully achieve the aims and objective, this thesis has been divided into six chapters including this introductory chapter. Chapter 1 is the introductory chapter which covers the present national and international status of the prosthetic devices, particularly in electronic knee. The limitation of the existing devices leading to the development of newer and sophisticated devices is discussed with some light on history of prosthesis. Importance of prosthetic biomechanics and emphasis to establish new linkages between gait analysis and prosthetic development and performance quantification are discussed. Gait analysis can be used in
prosthetic design and development, control parameter identification and for performance quantification of the prosthetic device. Fundamentals of gait analysis with various instrumentation techniques and measurement system have been discussed and technological status of prosthetic knee is reviewed. This chapter wraps up by defining the research aim and objective to be fulfilled in the thesis.

Chapter 2 - Literates about gait analysis, techniques and instrumentation for kinematic and kinetic and physiological assessments. Extensive literature survey is done and work carried out in the field is reported to find the technological gaps in the technology and techniques already developed by researcher. The literature findings are categorized into prosthetic biomechanics, gait analysis and sensor and instrumentation for prosthetic control. The use of biomechanics for prosthetic development and quantification and their further use in development of low cost sophisticated prosthetic technology are discussed. Research papers were thoroughly analysed for similar development carried out in the past and their limitations and advantages over the other methodologies adopted. Research on sensor and instrumentation system to capture gait control parameter sensing for dynamic feedback and their real time control through intelligent controllers are also reported.

Chapter 3- This chapter discusses kinematics for prosthetic development. In depth details of camera motion gait analysis techniques is presented using active and passive marker systems. The technological limitation of two technologies are discussed, which motivates to develop a hybrid using active marker based gait measurement system. Fabrication of LED based active marker along with required electronics and camera setup has been discussed for data acquisition. Through explanation of image analysis algorithm using LabVIEW Vision development platform has been given. Offline analysis of human walk has been carried out to measure seven spatio-temporal parameters of human gait using the developed algorithm.

Chapter 4- This chapter discusses kinetic gait assessment using force platform for prosthetic development. Role of ground reaction force components with variable walking speed of normal individuals is analysed. The importance of symmetry index between normal legs (left and right) has been established with variable walking speed. This analysis is extended with subjects wearing different types of footwear and barefoot. The chapter concludes with the development of indigenous force plate using an innovative potentiometer sensor for ground reaction
measurement. The static and dynamic calibration techniques are implemented to calibrate the developed force plate.

Chapter 5 – This chapter describes the strategy for EMG based prosthetic device control using surface electrodes. Explanation about EMG basics, the types of electrodes used to acquire EMG and feature extraction of EMG signals is presented. Based on the mechanical function of various muscles of lower limb for movement, sites for electrode placement are selected. Extensive experiments with surface EMG were carried out to visualize the effects of EMG amplitude and frequency over walking speed on level ground and treadmill. Sub-phasic analysis of EMG is carried out to study the EMG activity generated and to act as standard reference database of Indian ethnicity. The strategy is generated for EMG based electronic knee control using EMG from normal leg limb and knee flexion angle of amputated leg.

Chapter 6 – This chapter deals with the implementation of indigenous electronic knee joint. The mechanical design and electro-pneumatic control mechanism using a self designed motor valve control assembly is explained. In-house development of sensor mechanisms for knee flexion angle and gait phases is discussed. Potentiometer based electrogoniometer is tested and calibrated for slow, normal and fast walking of different individuals. Force sensitive resistor and accelerometer sensor mechanism are employed to detect stance phase and its duration. Various control approaches are implemented and discussed to reach optimal closed loop control mechanism. Embedded control system using RISC processor and software algorithm for various operating modes are discussed.

Chapter 7 – This is the concluding chapter, discussing the conclusions derived from the experimental results for kinematic, kinetic and SEMG assessment of gait of normal subjects. The linkage of gait analysis and its use in the developed prosthetic is elaborated. The results of experimental work carried out fulfill the aim and objectives earmarked. The sample size and other limitations of the present work can be overcome with the shown future directions in this chapter.