DESIGN AND IMPLEMENTATION OF A VISION BASED MOTION CAPTURING APPARATUS FOR HUMAN GAIT ANALYSIS

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Department of Electrical Engineering, University of Moratuwa
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degree of Master of the Science

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Abstract

Walking results from a complicated process involving the brain, spinal cord, peripheral nerves, muscles, bones and joints. Gait analysis is the systematic study of human walking. Gait analysis is often important for clinical gait assessment. Study of biological systems like human walking has paved the way for the development of various biomechanical systems like robot locomotion system.

This research proposes a low cost methodology to capture human gait cycle information. As the first step it was required to identify the important movements of the leg during walking. A study of human anatomy and biomechanics enabled this identification. Secondly, it has to be investigated what methodology to be followed to capture identified important movements of the leg during walking. For the study of human gait a spectrum of methodologies are being used throughout the world ranging from the absence of technological aids, at one extreme, to the use of complicated and expensive equipment at the other.

Through a study on various techniques used to capture motion, and after comparing these methods it was decided that multi-view marker based system is suitable for the requirement. This vision based methodology had the advantage that it can provide accurate motion information with low cost hardware and readily available software. When the two camera model is selected among other alternatives, it had to be studied how the pixel data obtained from motion capture are converted to the 3D spatial coordinates. Through a series of techniques, camera calibration, stereo calibration and triangulation, conversion of pixel data to 3D spatial coordinates was done. Based on this study the motion capture set up was created and motion capture was done.

The results obtained of the two camera model, camera parameters and parameters of the stereo system are presented in this thesis. Validation of the human gait cycle information obtained from this technique was done by comparing this information with gait pattern obtained with more accurate and sophisticated techniques.

DECLARATION

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

UOM Verified Signature

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S. A. P. Jinadasa

Date 25/02/2011

I endorse the declaration by the candidate.

UOM Verified Signature

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Dr Rohan Munasinghe

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Punsiri Jinadasa

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Chapter 1

Introduction

Human walking can be defined as 'a method of locomotion involving the use of the two legs'. Walking is accomplished through a complex and coordinated pattern of nerve signals, sent to the muscles, which in turn move the joints, the limbs and the remainder of the body.

Gait analysis is the systematic study of human walking. Since gait is a mechanical process which is performed by a biological system, gait analysis has become a part of scientific discipline Biomechanics. Gait analysis is often important for clinical gait assessment. A patient having walking disorder may be subjected to physical examinations by a therapist to identify the cause of the disorder. Also we often find patients who have previously undergone surgery on leg and gait pattern has not returned back to normal. To have a formal gait assessment, it requires a careful examination of the gait, using a systematic approach. Therefore, gait analysis is important to make detailed diagnoses in individuals with conditions affecting their ability to walk.

By studying this type of mechanical systems of biological systems one can get important information which is helpful in developing similar mechanical systems. Gait analysis has been used in robotics in designing of robot locomotion system [1]. Vital information revealed from gait analysis can be very helpful in scientific researches for designing artificial leg for a person who has lost his lower limb due to some reason.

1.1 Motivation

Throughout the history, techniques used for gait analysis have been evolved significantly. Today, gait analysis has developed to a stage of commercial exploitation and clinical application and is meeting increasing clinical interest. Presently, clinical gait assessment using instrumented systems is not widely practised in Sri Lanka. In developed countries there are laboratories set up especially for clinical gait assessment that are equipped with latest instrumentation.

Also vision based motion capture methods have wide range of applications. In visual media, computer-animated human characters and 3D reconstruction are widely used these days [18]. Stereo vision with depth calculation is used in robotics, robot control and machine vision.

1.2 Significance of the Research

In Sri Lankan context there is a segment of people who could benefit from instrumented gait assessment. The patients having walking disorders and patients who have undergone surgery on legs fall into that segment. Presently, these people have to go to test laboratories outside Sri Lanka to get their gait pattern assessed. If this assessment can be done locally it will facilitate local surgeons and medical experts to perform their diagnosis and treatment locally.

With the increasing usage of above applications of vision based motion capture, there is large number of research work going on in this study area. Theoretical background of this research opens up avenues for other research areas of vision based motion capture.

1.3 Objectives and Scope

Objective of this research is to present a low cost vision based system for motion capture. The motion capture technique presented focuses on capturing the motion of human gait pattern. This technique is not aimed at capturing all the movements of the human leg during walking but focuses only on significant movements of the leg.

First it was required to decide which methodology is suitable for the motion capture. A literature survey was carried out to investigate available motion capture techniques for human gait analysis. Various researchers have developed different methodologies to determine gait parameters. Video recordings, Photographic systems, Active marker systems, multiple calibrated camera systems are few methods used by different personnel involved in gait studies. When selecting apparatus for the selected technique, cost involvement was kept minimal by using commonly available equipment.

1.4 Achievements

A feasible methodology to capture the gait information was identified from this work, which is a method employing low cost cameras for motion capture. This work presents a frame work that can be used for motion capture which can be developed to an autonomous motion capture technique by incorporating image processing techniques and other specific algorithms. Since no sophisticated equipments were used in the presented technique, accuracy of the motion capture results were needed to be verified against published motion capture results obtained using high accurate equipments and validation results are presented in this work.

1.5 Outline of the Thesis

The thesis has been organized in eight chapters. Chapter 1 provides the background of the research that covers the motive behind the work, the importance and benefits of the research and the final achievement. It indicates the scope within which the research was formulated and identifies objectives of the research.

Chapter 2 discusses the foundation for the work concerned, the anatomy of leg and biomechanics of human gait. This chapter describes the exact motions of the leg that were analysed using the presented technique.

Results of the literature survey on various motion capture techniques and the rationale behind selecting the proposed technique is given in Chapter 3.

The theoretical background of the proposed motion capture method is discussed in Chapter 4. Implementation of the design is explained in Chapter 5. In Chapter 6 validation of the apparatus for motion capturing of human gait is done. The result of the work is discussed in Chapter 7.

Chapter 2

Biomechanics of Human Gait

Human gait is a mechanical process which is performed by a biological system. When this mechanical system is analysed it has to be interpreted with respect to the biological system. Therefore it is important to know the biological aspect of human gait and its terminology. When selecting an appropriate method for motion capture of human gait, the joints or bones which have any sort of movement has to be identified. After that a decision is to be made as to what are the exact movements of the leg that is to be analysed using the proposed technique. Accordingly, there will be some critical points on the leg where it is important analysing the movement. This was accomplished by studying biomechanics and anatomy. Therefore this chapter is mainly focused on introducing biological aspects of human walking.

2.1 Planes of the Body

In bio-mechanic studies, there are certain anatomical terms to describe the relationship between different parts of the body and to describe certain movements of the body.

Sagittal plane, Transverse Plane and Frontal Plane are the reference planes used to describe motion of the limbs. These planes are illustrated in Fig 2.1.

1) Sagittal pane is any plane which divides part of the body into right and left portions.
2) A frontal plane divides a body part into front and back portions
3) A transverse plane or horizontal plane divides a body part into upper and lower portions

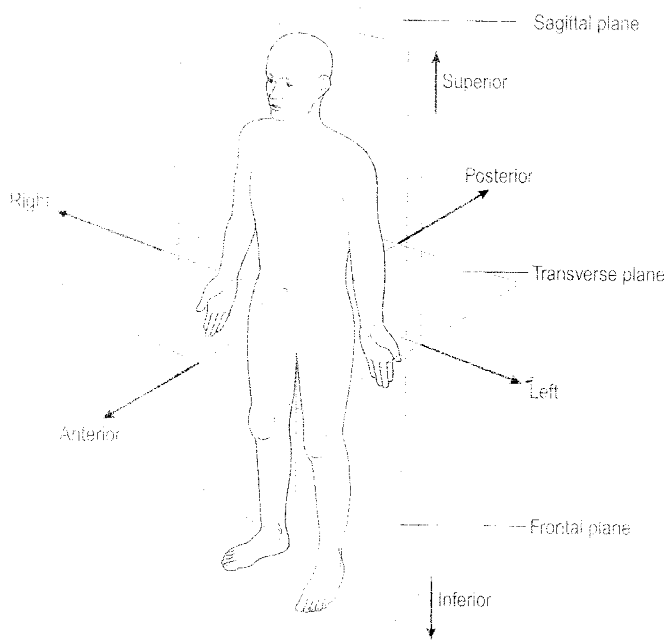

Fig 2.1: The anatomical position, with three reference planes (Source: Gait Analysis an Introduction by Michael W. Whittle)

Hip, Knee ankle and foot are the joints that move during walking. Movements of these joints take place in the described planes above,

1) Flexion and extension take place in the sagittal plane; in the ankle these movements are called dorsiflexion and plantarflexion, respectively.
2) Abduction and adduction take place in the frontal plane
3) Internal and external rotation take place in the transverse plane; they are also called medial and lateral rotation respectively, the term referring to the motion of the anterior surface.

As indicated in the Fig 2.2 during gait, important movements occur in all three planes – sagittal, frontal and transverse. Largest movements occur in sagittal plane [2].

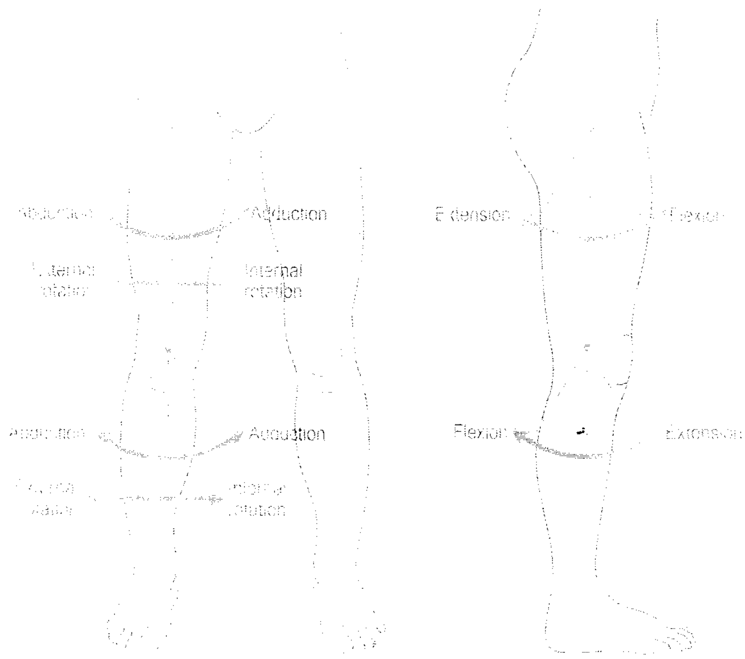

Fig 2.2: Movements about the hip joint and knee joint (Source: Gait Analysis an Introduction by Michael W. Whittle)

2.2 Bones of the Lower Limb

Bones of the lower limb are illustrated in Fig 2.3.

2.2.1 Pelvis

Bones of the pelvis and legs are the bones that play a major role in walking. For the practical purposes of gait analysis, pelvis can be considered as a single rigid structure even though it is constructed by fusion of multiple bones [2].

2.2.2 Femur

Femur is the longest bone in the body. The spherical femoral head articulates with the pelvic acetabulum to form the hip joints. From the hip joints this bone continues to knee joint.

2.2.3 Patella or knee joint

This bone is embedded within a tendon. Its posterior surface articulates with the anterior surface of the lower end of the femur to form the patellofermoral joint. The patella has an important mechanical function, which is to displace the quadriceps tendon forwards, thereby improving its leverage.

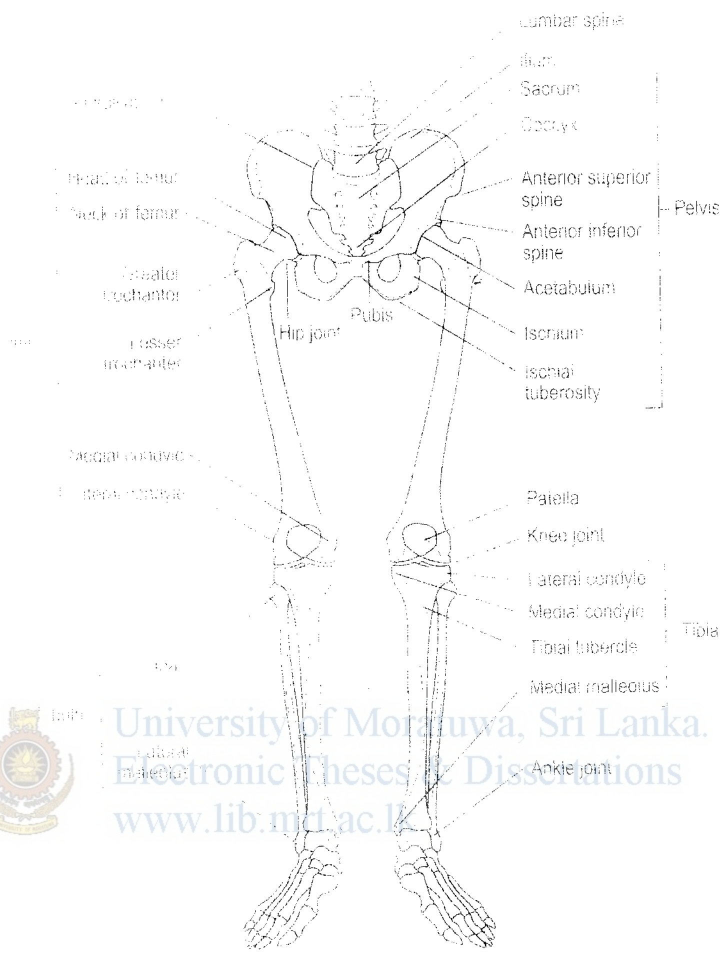

Fig 2.3: Bones and joints of the lower limbs (Source: Gait Analysis an Introduction by Michael W. Whittle)

2.2.4 Tibia and fibula

Tibia extends from the knee joint to the ankle joint. Fibula is next to the tibia on its lateral side. For most of its length it is a fairly slim bone. The tibia and fibula are in contact with each other at their upper and lower ends.

Movement of these joints are very small and can be neglected [2].

2.2.5 Foot

The foot is a very complicated structure. Foot is made of three parts, the hindfoot, midfoot and forefoot. The talus is the upper bone of the foot which forms the ankle joint.

2.3 Joints of the Lower Limb

A joint occurs where one bone is in contact with another. In certain joints a significant amount of movement can take place and certain other joints only small movements can occur. A synovial joint is a type of a joint where fairly large movement can take place. In a synovial joint, the bone ends are covered in cartilage and the joint is surrounded by a synovial capsule, which secretes the lubricant synovial fluid.

Joints of the lower limb are illustrated in Fig 2.3.

2.3.1 Hip joint

Hip joint is the only true ball-and-socket joint in the body, the ball being the head of the femur and the socket the acetabulum of the pelvis. This joint is capable of flexion, extension, abduction, and adduction, internal and external rotation as shown in Fig 2.2.

2.3.2 Knee joint

The knee joint consists of the medial and lateral condyles of the femur, above, and the corresponding condyles of the tibia, below. The motion of the joint is controlled by five legaments which, between them, exert very close control over the movement of the knee. In the normal individual, the motions of the knee are flexion and extension, with a small amount of internal and external rotation. Significant amounts of abduction and adduction are only seen in damaged knees. As the knee comes to full extension, there is an external rotation of a few degrees: the so-called automatic rotation or 'scre-home' mechanism [2].

2.3.3 Ankle joint

Ankle joint has three surfaces: upper, medial and lateral. The upper surface is the main articulation of the joint; it is cylindrical and formed by the tibia above the talus below. The medial joint surface is between the talus and the inner aspect of the medial malleolus of the tibia. Correspondingly, the lateral joint surface is between the talus and the inner surface of the lateral malleolus of the fibula [2].

The ankle joint being cylindrical has only one significant type of motion, dorsiflexion and plantarflexion, corresponding to flexion and extension in other joints [2].

2.4 Significant Movements of the leg during gait

A tabulated summary of the above explanation about the movements of the leg during walking is sh78own in the Table 2.1.

	Sagittal Plane Movements		Frontal Plane Movements		Transverse Plane	
	Flexion	Extension	Abduction	Adduction	Internal Rotation	External Rotation
Hip Joint	Large		Small		Small	
Knee Joint	Large		No		Small	
Ankle Joint	Large		No		No	

Table 2.1: Movements of the Leg during Walking

From this summary it is evident that largest movement of the leg takes place in the Sagittal plane in all three joints under consideration.

In this study the movement of the muscles are neglected. Also the toe joint is not considered for the motion capture as the movement of the toes with respect to toe joint is small.

Chapter 3

Motion Capturing Techniques

When considering the methods which may be used to perform gait analysis, it is helpful to regard them as being in a 'spectrum' or 'continuum', ranging from the absence of technological aids, at one extreme, to the use of complicated and expensive equipment at the other [3], [4]. Selection of a method is to be done considering the purpose of analysis.

In this analysis the gait motion capture method has to fulfil certain requirements.

1) It has to give a permanent record of data
2) Has to be fast to capture high-speed events
3) Data has to be in a format which provides the 3D positions of moving leg or joint angles in absolute terms

By studying the alternative methods available for gait analysis, a selection was made as to which method to be used for this study. Cost of the apparatus, Availability of the apparatus, non-invasiveness and accuracy were considered as the key selection criteria.

3.1 Direct Motion Measurement Systems

Direct motion measurement systems measure the motion of the leg using some form of direct connection to the subject. In this method Electrogoniometers are used to measure joint angle variations [4]. Electrogoniometer is a device that can be used for making continuous measurements of the angle of a joint. Fig 3.1 illustrates how goniometers are fixed on a subject's leg to take measurements.

3.1.1 Potentiometer devices

Potentiometer devices can be used to measure the angle of a joint if it is fixed in such a way that the body of the potentiometer is attached to one limb segment and the spindle to the other. The device can be calibrated to measure the joint angle in degrees. Multiple potentiometers can be mounted in different planes to make multi-axial measurements. Another similar device is rotary encoder that can be used for angle measurement.

Fig 3.1: Subject wearing tri-axial goniometry (Source: Gait Analysis an Introduction by Michael W. Whittle)

3.1.2 Flexible Strain Gauges

Flexible strain gauge electrogoniometer consists of a flat, thin strip of metal, one end of which is fixed to the limb on each side of the joint being studied. The bending of the metal as the joint moves is measured by strain gauges and the electronics. The output depends on the angle between the two ends [2], [5]. Fig 3.2 illustrates use of flexible strain gauges in joint angle measurement.

Fig 3.2: Subject wearing flexible strain gauges (Source: Gait Analysis an Introduction by Michael W. Whittle)

The main drawback of direct motion measurement systems is that the measuring devices inhibit the motion of the subject [4]. Also the measurements are in relative angles. Due to these reasons the direct measurement system is not considered.

Availability of Apparatus	The available measuring device is rotary encoder
Cost of the Apparatus	Cost of rotary encoders is on the average side
Accuracy	Good accuracy is expected but method of fixing encoders to the joints is an issue
Non-invasiveness	Attached encoders is a hindrance for walking

Table 3.1: Selection criteria applied to direct motion capture method

3.2 Kinematic Systems

Kinematics is the measurement of movement or geometric description of motion, in terms of displacements, velocities and accelerations. Kinematic systems are usually based on optical motion capture. Optical motion capture can be further classified according to the number of views, monocular or multi-view. Kinematic methods can also be divided to marker-based or marker-less methods. A marker based systems measures the trajectories of target points (markers) on the body [6].

3.2.1 Two Dimensional kinematic systems (monocular, marker based system)

Kinematic measurement may be made in either two dimensions or three. Simplest kinematic measurements are made using a single camera, in an un-calibrated system. Such a system can be used to measure joint angles in the sagittal plane. The camera is positioned at right angles to the plane of motion and as far away as possible, to minimize the distortions introduced by perspective.

Monocular techniques have to deal with ambiguities in the reconstruction of 3D pose caused by reflective ambiguity [7] and kinematic singularity [8].

Availability of Apparatus	Video cameras, camcoders or webcams are widely available
Cost of the Apparatus	Cost of above cameras is on the average side
Accuracy	Accuracy is less because of single camera system
Non-invasiveness	No hindrance for the subject's walking

Table 3.2: Selection criteria applied to two dimensional kinematic systems

3.2.2. Three dimensional kinematic systems (multi-view, marker based system)

To achieve reasonable accuracy in kinematic measurement, it is necessary to use a calibrated three-dimensional system, which involves making measurements from more than one viewpoint. Different types of cameras can be used to capture the images from different viewpoints. From the synchronized images, 3D positions of the markers can be extracted after processing. Software for calibration of multi-cameras have been developed by different vendors of camera systems [17].

Availability of Apparatus	Video cameras, camcoders or webcams are widely available
Cost of the Apparatus	Cost of above cameras is on the average side
Accuracy	Good accuracy can be expected from multi-view 3D kinematic system
Non-invasiveness	No hindrance for the subject's walking

Table 3.3: Selection criteria applied to three dimensional kinematic systems

3.2.2.1 Photographic systems

The advantages of photographic systems are the relatively low cost of the equipment, the potentially high accuracy obtainable and the ability to film subjects 'in the field', rather than in the laboratory.

Here the subject is filmed while walking; using one or more cameras and the calibration object is also filmed, without altering the camera position or settings. After the film or films have been processed, the images are digitized by an operator, who views successive frames, identifies the required landmarks and measures their two-dimensional coordinates [2], [9]. Using a specially designed 'analyzing projector' the operator moves a cursor to the appropriate points in the image and presses a button to transfer the coordinates of each point into a computer. To avoid frame-to-frame variations in film position, it is common also to digitize the positions of fixed markers within the field of view [2].

3.2.2.2 Videotape and DVD digitizers

The same way photography has been used, videotape and DVD digitizers have considerable advantages in terms of cost, convenience and speed, although it may not be quite as accurate, because of the poorer resolution of television image compared with cine film and further losses involved in recording and replaying the images. Another considerable advantage is that it is possible to automate the digitization process using electronic processing of the image, especially if skin markers are used, which show up clearly against the background [2], [9].

3.2.2.3 Television / computer systems

In this approach, reflective markers are fixed to the subject's limbs, either close to the joint centres or fixed to limb segments in such a way as to identify their positions and orientations. Close to the lens of each television camera is an infrared or visible light source, which causes the markers to show up as very bright spots. Each television camera is connected to a special interface board which analyzes each television frame. The systems differ in how they locate the 'centroid' or geometric centre of each marker within the television image, but it is typically calculated using the edges of any bright spots in the field of view. The computer stores the marker centroids from each frame of data for each camera, but initially there is no way to associate a particular marker centroid with a particular physical marker, The process of identifying which marker image is which for each of the cameras, and of following the markers from one frame of data to the next, is know as 'tracking' or 'trajectory following'. The speed and convenience of this process differ considerably from one system to another and also between software options from a single manufacturer. Beyond their use in gait analysis, they are increasingly used to provide the input for computer graphic systems, in the video game and motion picture industries [10].

3.2.2.4 Active marker systems

Another type of kinematic system uses active markers, typically light-emitting diodes (LED's) [8], and a special optoelectronic camera. Typically, these systems use invisible infra-red radiation. The camera measures the position of the marker by analyzing the light coming from it, using either two dimensional or one-dimensional cameras.

The LEDs are arranged to flash on and off in sequence, so that only one is illuminated at any instant of time. The cameras are thus able to locate each marker in turn, without the need for a 'tracking' procedure to determine which one is which. The penalty for this convenience is the need for the subject to carry a power supply, with wires running to each of the marker. Problems may also occur because the the camera records not just the light from the LEDs, but any other light which falls on it [11].

3.3 Marker-less, Multi-view Motion Capture

Marker-less motion capture systems computes motion parameters from extracted silhouettes or other features (eg edges) [9], [12].

In this method human motion is captured as video data from multiple cameras subjects' kinematics is extracted in three dimensions using specific algorithms [2]. Various technical papers are published about this subject, researchers developing different kinds of algorithms.

Availability of Apparatus	Video cameras, camcoders or webcams are widely available
Cost of the Apparatus	Cost of above cameras is on the average side, Cost of software is high
Accuracy	High accuracy can be expected from multi-view marker-less motion capture depending on the accuracy algorithms used
Non-invasiveness	No hindrance for the subject's walking

Table 3.4: Selection criteria applied to Marker-less, Multi-view Motion Capture

3.4 Kinematic Motion Capture System Combined with Force Information

This method uses kinematic motion capture system combined with a force platform. Force platform is a specially made steel plate where force exerted on it is detected by transducers at its corners and is converted to electrical signals that is amplified and recorded [11]. The capability of the combined system is greater than that of the sum of its component parts [2]. The reason for this is that if the relation ship is known between the limb segments and the ground reaction force vector, it is possible to perform 'inverse dynamic' calculations, in which limb is treated as a mechanical system. Set up of this type of motion capture is shown in Fig 3.3.

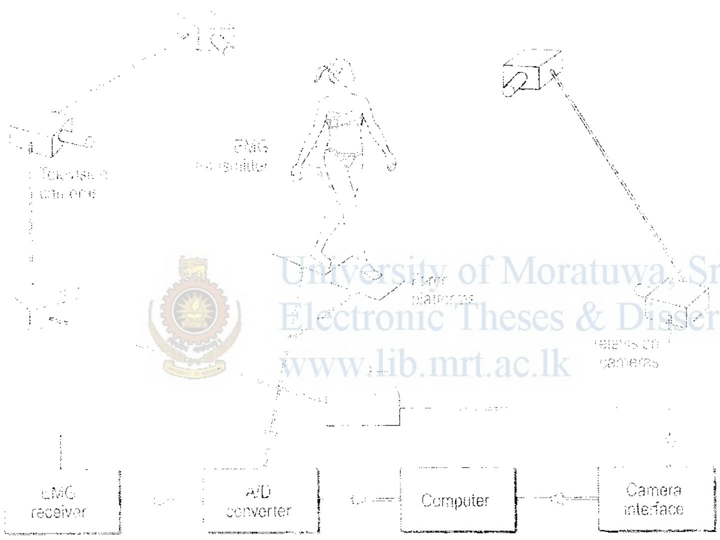

Fig 3.3: Six camera kinematic system (Source: Gait Analysis an Introduction by Michael W. Whittle)

Availability of Apparatus	Video cameras, camcoders or webcams are widely available, force platforms are not available
Cost of the Apparatus	Cost of above cameras is on the average side, cost of other equipment is very high
Accuracy	High accuracy can be expected from multi-view 3D kinematic system with combined force information
Non-invasiveness	No hindrance for the subject's walking

Table 3.5: Selection criteria applied to kinematic motion capture systems combined with force information

3.5 Selection of Motion Capture Method

As explained above the selection of the appropriate method for motion capture was done based on four criteria. When compared with those, the appropriate selected method was the 3D kinematic (multi-view, marker based) system. The number of view points to be used is subjective to the nature of the motion to be captured.

In this system another selection was to be made with respect to the apparatus used for motion capture.

First the selected motion capture apparatus was video camera. This method was developed for motion capture of human gait cycle but the results were not satisfactory. Details of this failed technique are illustrated in Chapter 7 under "Practical problems faced during the implementation".

Motion capture apparatus selected secondly was webcams. As the objective of the research is to capture only of the sagittal plane movements of the leg, the number of webcams was limited to two.

The reasons for selecting vision based system consisting of two webcams are given below,

1) Webcams are commonly available
2) Cost of the apparatus is not excessively high
3) As the research is not aimed at very high accuracy and does not require sophisticated instrumentation for this purpose.
4) Camera calibration is straight forward
5) Camera calibration software is freely available

Chapter 4

Proposed Motion Capture Technique

The selected technique for motion capture is marker based kinematic system, motion capture apparatus being two webcams. The required resources to acquire multi-view image data involve capture room, body suit, camera equipment and an acquisition system [6]. Capture room was prepared to have a good lighting level in order to have marker locations easily identified from the captured images. The locations of the markers on the suit are designed such that the movement of joints can be extracted from the identification of movement of the markers placed on the leg. HP Webcam 101 is the webcam model. As acquisition system the laptop computers were used. Here, software "Cyberlink Youcam" is used which enabled the captured clips to save in the laptop computer hard disk.

This chapter lays down the arrangement of the motion capture system and the theoretical back ground of the system.

4.1 Physical Arrangement of the System

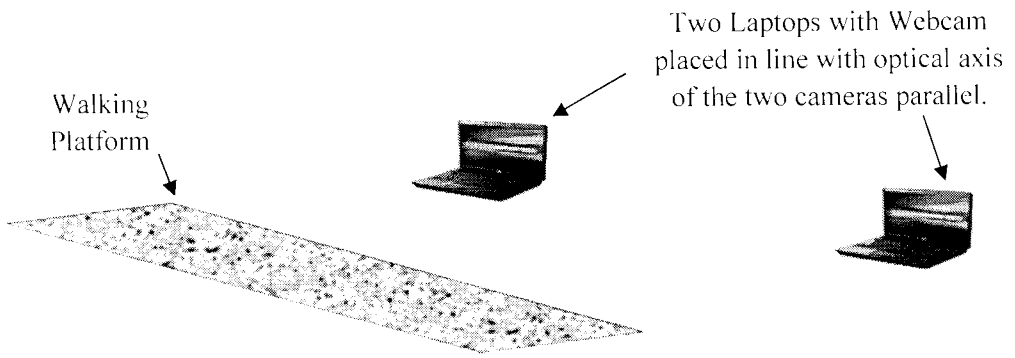

Fig 4.1: Arrangement of Motion Capturing Apparatus

Fig 4.1 illustrates the arrangement of the apparatus set up for motion capture. The two webcams were placed parallel to the walking platform. The distance from the walking platform to the camera was adjusted so that the full image of the leg can be obtained from both cameras at the same time thorough out the gait cycle of the walking subject.

4.2 Functional Block Diagram

Fig 4.2 represents the arrangement of the basic activities planned to do for the motion capture of human gait.

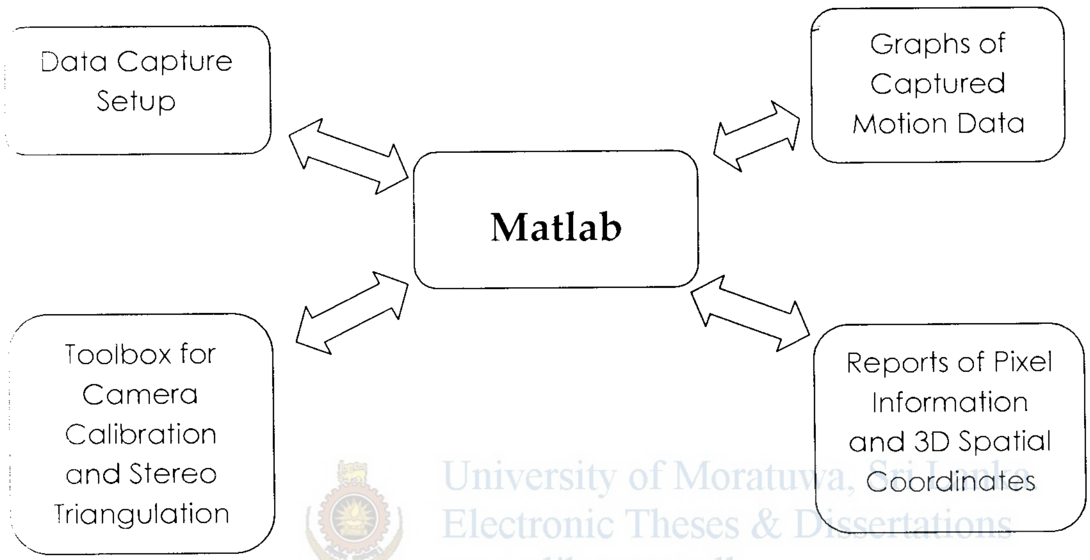

Fig 4.2: Functional Block Diagram

4.2.1 Matlab

The software used for all the data capture and analysis is Matlab. For camera calibration, to extract pixel information from images and 3D coordinate identification of markers were done using Matlab.

4.2.2 Data capture setup

For data capture the hardware had to be arranged so that the correct image or clip is taken for the analysis. In this case low cost motion capture hardware was used which consist of two laptop computers with Webcam feature.

4.2.3 Reports of pixel information and 3D spatial coordinates

Tables of pixel information and 3D spatial coordinates were prepared at various stages of the project.

4.2.4 Graphs of captured motion data in Excel

The results, that is, 3D spatial coordinates of the markers were transferred to Excel where graphs of joint angle variations and other graphs for further analysis of data were done.

4.3 Theoretical Background of Geometry of 3D Vision

The main objective of the vision based camera system is, motion capturing of the human leg movements and transfer that motion information to 3D movements with respect to a world co-ordinate system. Fig 4.3 describes how the captured data were converted to the desired outcome of the research.

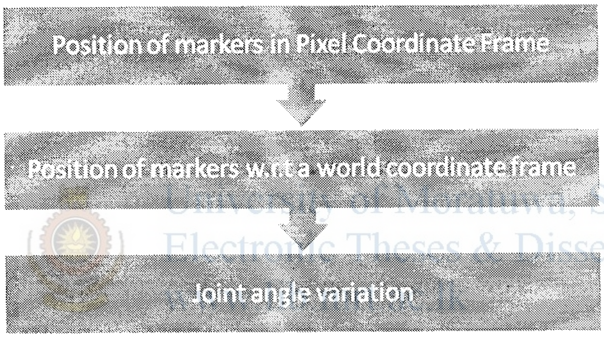

Fig 4.3: Stages of data processing

To find out the relationship between pixel co-ordinates and world co-ordinates some theoretical background was required about Geometry of 3D vision.

Fig 4.4 indicates the geometry of a linear perspective camera. Camera is assumed to be with a thin lens and pinhole camera arrangement is assumed for building up the abovementioned relationship between pixels and the 3D representation of them [13], [14].

The plane on the bottom is the image plane to which the real world projects and the vertical dotted line is the optical axes. The lens is positioned perpendicular to the optical axis at the focal point C. Focal length f is a parameter of the lens. The projection is performed by an optical ray reflected from the scene point X. the optical ray passes through the optical center C and hits the image plane at the point U.

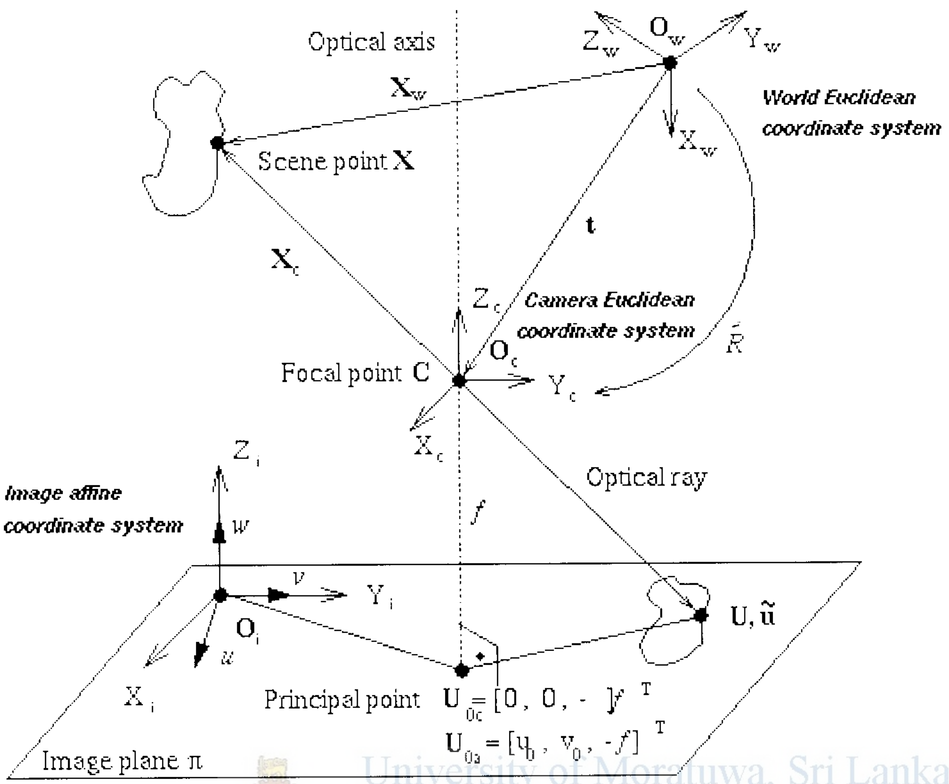

Fig 4.4: Geometry of a Linear Perspective Camera

Following co-ordinate systems can be defined,

1) The world Euclidean co-ordinate system (subscript-w) has origin at the point Ow.

2) Camera Euclidean co-ordinate system (subscript-c) has the focal point C=Oc as its origin.

3) The image affine co-ordinate system (subscript-i) has axes aligned with the camera co-ordinate system, with Xi, Yi lying in the image plane.

4) The image affine co-ordinate system (subscript-a) has co-ordinates axes u,v,w and origin Oi coincident with the origin of the image Euclidean co-ordinate system.

4.3.1 World co-ordinates to camera co-ordinates

A Scene point X is expressed in the world Euclidean co-ordinate system as a 3x1 vector as in equation 4.1. To express the same point in the camera Euclidean co-ordinate, ie Xc, we have to rotate it as specified by the matrix R and translate it by subtracting vector t.

$$X_c = \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = R(X_w - t) \qquad (4.1)$$

R and t consist of six parameters called extrinsic camera parameters.

4.3.2 Camera co-ordinate system to image plane

The point Xc is projected to the image plane pi as point Uc. The x and y co-ordinates of the projected point can be derived from the trigonometry (equation 4.2).

$$U_c = \begin{bmatrix} \frac{-f x_c}{z_c} \\ \frac{-f y_c}{z_c} \\ -f \end{bmatrix} \qquad (4.2)$$

4.3.3 Image Euclidean co-ordinate system to image affine co-ordinate system

Homogeneous co-ordinates can be expressed in affine transformation as a multiplication by a single 3x3 matrix where unknowns a, b & c describe the shear together with scaling along co-ordinate axes, and u_0 and v_0 give the affine co-ordinates of the principle point in the image.

$$u' = \begin{bmatrix} U \\ V \\ W \end{bmatrix} = \begin{bmatrix} a & b & -u_0 \\ 0 & c & -v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{-f x_c}{z_c} \\ \frac{-f y_c}{z_c} \\ 1 \end{bmatrix} \qquad (4.3)$$

4.3.4 Camera calibration matrix

Multiplying by z_c the equation simplifies to,

$$z_c u = \begin{bmatrix} -fa & -fb & -u_0 \\ 0 & -fc & -v_0 \\ 0 & 0 & 1 \end{bmatrix} R(X_w - t) = KR(X_w - t) \qquad (4.4)$$

K is termed camera calibration matrix or camera matrix.

The coefficients of this matrix are called Intrinsic Camera Parameters.

4.3.5 Physical explanation of intrinsic camera parameters

$$u = \frac{U}{W} = -f_a \frac{x_c}{z_c} - f_b \frac{y_c}{z_c} - u_0 = \alpha_u \frac{x_c}{z_c} + \alpha_{shear} \frac{y_c}{z_c} - u_0 \qquad (4.5)$$

$$v = \frac{V}{W} = -f_c \frac{y_c}{z_c} - v_0 = \alpha_v \frac{y_c}{z_c} - v_0 \qquad (4.6)$$

α_u represents scaling in the u axis, measuring focal length in pixels along u axis.

α_v similarly specifies f in pixels along the v – axis

α_{shear} is the coefficient defining the angle between u and v pixel axis.

v_0 and u_0 give the affine co-ordinates of the principle point in the image.

Above five parameters encompass focal length, image format and principal point.

Focal length and principle point were explained earlier. Image sensor format of a digital camera determines the angle of view of a particular lens when used with a particular camera. Angle of view describes the angular extent of a given scene that is imaged by a camera. Image sensor is the device that converts an optical image to an electric signal [15]. [17].

4.4.6 Camera calibration

When a camera is used, light from the environment is focused on an image plane and captured. This process reduces the dimension of the data taken in by the camera from the three to two (light form 3D scene is stored on a 2D image). Each pixel on the image plane therefore corresponds to a shaft of light from the original scene. Camera calibration determines which incoming light is associated with each pixel on the resulting image. In an ideal pinhole camera, a simple projection matrix is enough to do this. This transformation can not be described perfectly by a perspective transformation because of distortions which occur between points on the object and the location of the images of those points. These distortions can be modeled. with more complex camera systems, errors resulting from the misaligned lenses and deformations in their structures can result in more complex distortions in the final image.

Camera calibration is the process of finding the true parameters of the camera that produced a given photograph or video. Nonlinear intrinsic parameters such as lens distortion are also important although they cannot be included in the linear camera model described by the intrinsic parameter matrix. Many modern camera calibration algorithms estimate these intrinsic parameters as well.

There are number of techniques for camera calibration [17], [18], [19], [21]. The most common method is by using "Camera Calibration Toolbox for Matlab" published by Jean-Yves Bouguet. [13], [14].

4.3.7 Extrinsic parameters

R and t explained under 4.3.1 represent extrinsic parameters which denote that coordinate system transformation form 3D world coordinate to 3D camera coordinates. Equivalently, the extrinsic parameters define the position of the camera centre and the camera's heading in world coordinates [13], [15].

4.3.8 Camera calibration in stereo Vision

In stereo vision, two cameras take pictures of the same scene, but they are separated by a distance – exactly like our eyes. In computer stereo vision, the disparity at which objects in the image best match is used by the computer to calculated their distance [13], [15]. Stereo vision uses triangulation based on epipolar geometry to determine distance to an object.

4.3.9 Epipolar geometry

When two cameras view a 3D scene from two distinct positions, there are a number of geometric relations between the 3D points and their projections onto the 2D images that lead to constraints between the image points. These relations are derived based on the assumption that the cameras can be approximated by the pinhole camera model [13].

Fig 4.5 depicts two pinhole cameras looking at point X. In real cameras, the image plane is actually behind the focal point, and produces a rotated image. Here, however, the projection problem is simplified by placing a virtual image plane in front of the focal point of each camera to produce an un-rotated image. [illegible] and [illegible] represent the focal points of the two cameras. X represents the point of interest in both cameras. Points [illegible] and [illegible] are the projections of point X onto the image planes.

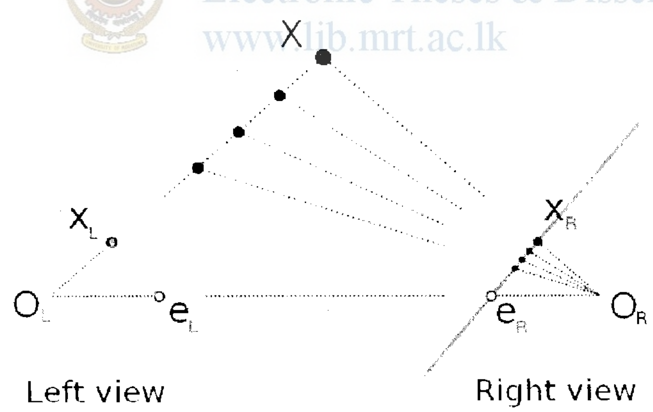

Fig 4.5: Epipolar geometry

Each camera captures a 2D image of the 3D world. This conversion from 3D to 2D is referred to as a perspective projection and is described by the pinhole camera model. It is common to model this projection operation by rays that emanate from the camera, passing through its focal point. Note that each emanating ray corresponds to a single point in the image [13], [15].

4.3.10 Epipolar point

Since the two focal points of the cameras are distinct, each focal point projects onto a distinct point into the other camera's image plane. These two image points are denoted by and and are called epipolar points. Both epipolar points in their respective image planes and both focal points and lie on a single 3D line.

4.3.11 Epipolar line

The line -X is seen by the left camera as a point because it is directly in line with that camera's focal point. However, the right camera sees this line as a line in its image plane. That line (-) in the right camera is called an epipolar line. Symmetrically, the line -X seen by right camera as a point is seen as epipolar line (-) by the left camera.

An epipolar line is a function of the 3D point X, ie. there is a set of epipolar lines in both images if we allow X to vary over all 3D points. Since the 3D line -X passes through camera focal point , the corresponding epipolar line in the right image must pass through the epipole (and corresponding for eippolar lines in the lft image). This means that all epipolar lines in one image must intersect the epipolar point of that image. In fact, any line which intersects with the epipolar line since it can be derived from some 3D point X [13], [15].

4.3.12 Epipolar plane

As an alternative visualization, consider the points X, & that form a plane called the epipolar plane. The epipolar plane intersects each camera's image plane where It forms lines – the epipolar lines. All epipolar planes and epipolar lines intersect the epipole regardless of where X is located [13], [15].

4.3.13 Epipolar constraint and triangulation

If the relative translation and rotation of the two cameras is known, the corresponding epipolar geometry leads to two important observations.

If the projection point x_L is known, then the epipolar line e_R - x_R is known and the point X projects into the right image, on a point x_R which must lie on this particular epipolar line. This means that for each point observed in one image the same point must be observed in the other image on a known epipolar line. This provides and epipolar constraint which corresponding image poins must satisfy and it means that it is possible to test if two points really correspond to toe same 3D point. Epipolar constraints can also be described by the essentioal matrix or the fundamental matrix between the two cameras.

If the points x_L and x_R are known, their projection lines are also known. If the two image points correspond to the same 3D point X the projection lines must intersect precisely at X. This means X can be calculated from the coordinates of the two image points, a process called triangulation [15].

4.3.14 Simplified cases

The epipolar geometry is simplified if the two camera image planes coincide. In this case, the epipolar lines also coincide (e_L-x_L = e_R-x_R). Furthermore, the epiplolar lines are parallel to the line (O_L-O_R) between the focal points, and can in practice be aligned with the horizontal axes of the two images. This means that for each point in one image, its corresponding point in the other image can be found by looking only along a horizontal line. If the cameras cannot be positioned in this way, the image coordinates from the cameras may be transformed to emulate having a common image plane. This process is called image rectification [13], [15].

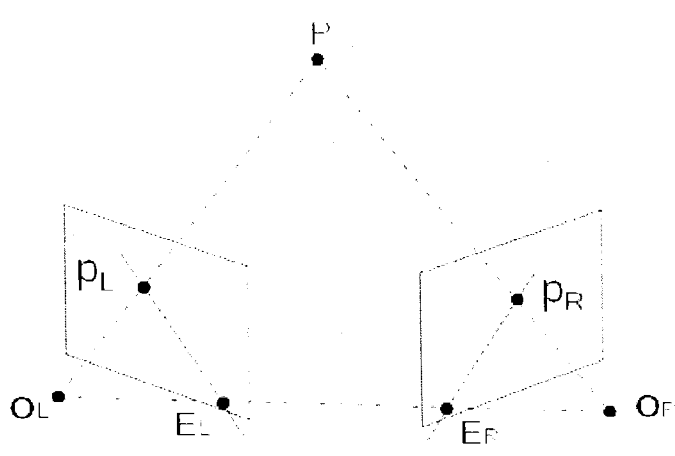

Fig 4.6: Simplified epipolar geometry

4.4 Camera Calibration Toolbox for Matlab

In extracting 3D locations of marker from 2D positions of markers in pixel co-ordinate frame, camera calibration toolbox for Matlab was used. Three important functionalities were used of this toolbox.

1) Camera calibration engine – Used to calibrate cameras
2) Stereo calibration engine – Used to calibrate the stereo system
3) Stereo triangulation function – Used to evaluate the 3D position of marker given the 2D position of markers in pixel co-ordinate frame

From the images taken by keeping a checkerboard in different orientations camera calibration of individual camera can be performed [16]. The calibration results were stored in Matlab memory of the two cameras. By running the stereo calibration engine parameters of the total stereo system can be found. Finally by running stereo triangulation, 3D locations of the markers can be found with respect to a camera co-ordinate frame by taking 2D positions of each marker as inputs.

Chapter 5

Implementation of the Design

As described in Chapter 3 the method used to capture gait data is the three dimensional measurement system involving two calibrated cameras. Following hardware was used.

1) Two Webcams (inbuilt to HP laptop computers)
2) Checkerboard (For camera calibration)
3) Subject wearing a black coloured body suit and markers pasted on it at predetermined locations where leg joints and bones are located
4) A straight iron rod about 6 feet high used as a reference height
5) An object for the subject to carry when to help synchronization of two cameras.

Following software was used.

1) Matlab 2008
2) Cyberlink Youcam
3) Camera calibration toolbox for Matlab
4) Motion to picture software

5.1 Data Capture

5.1.1 Preparation of the hardware and the subject for data capture

As the most of the movements of the leg takes place in the sagittal plane the data to be captured were also in sagittal plane. The two laptop computers having Webcam were placed parallel to the waking platform so that the axes of webcams are also parallel to each other similar to Fig 5.1. Lighting to the walking platform was adjusted so that the markers placed on the subject are clearly visible through the Webcam. Positioning of the two laptops and the subject was done, enabling for both Webcams to capture full height of the leg in one cycle of the subject's leg motion.

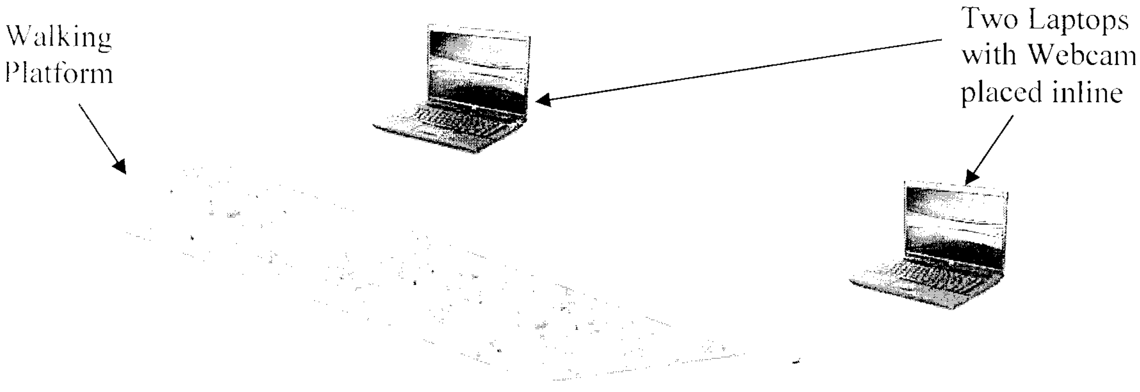

Fig 5.1: Data capture setup

5.1.2 Taking snap shots of the checkerboard

Checkerboard was placed at different orientations in front of the two Webcams and snap shots were taken at the same time from both cameras. These images were used to find out parameters of the camera system. Fig 5.2 shows two images taken of the checkerboard simultaneously.

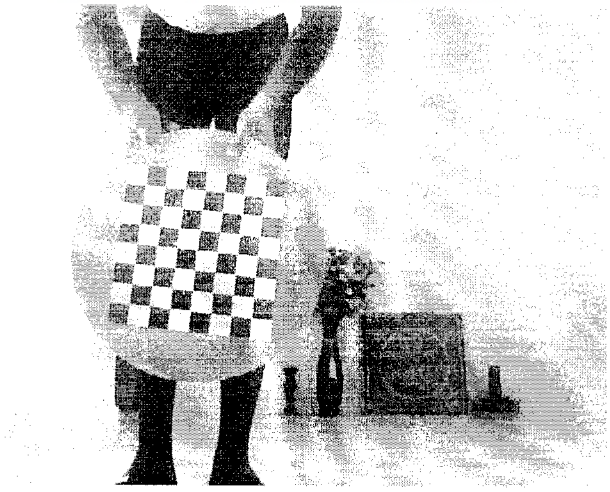

Fig 5.2: An image taken for camera calibration

5.1.3 Taking snap shots of the straight iron rod

Through the camera calibration and stereo triangulation 3D spatial coordinates can be derived of a point under vision by both cameras. Unit of this 3D spatial coordinates is pixels. To convert the 3D coordinates into metric units an iron rod with markers placed on it was used. The steel iron rod was placed on the walking path within the view span of the two cameras and images were taken from both cameras simultaneously as shown in Fig 5.3.

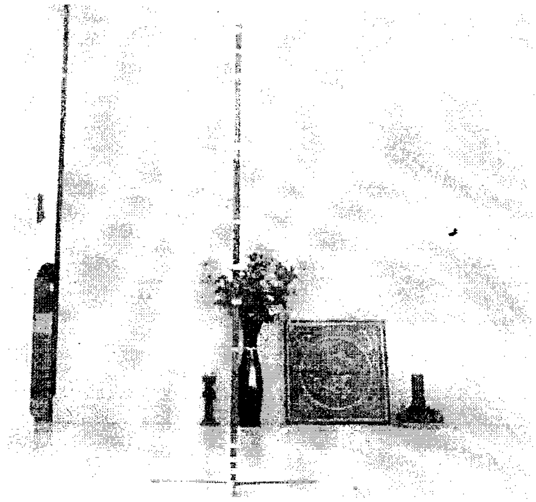

Fig 5.3: Image of marked iron rod

5.1.4 Recording of subject walking

When the subject is walking the clips were captured by the two Webcams simultaneously. These clips were later converted to images using motion to picture software like in Fig 5.4. For the synchronization purpose the subject was given an object hanging from a string to drop before he starts walking. After the clips were converted to images corresponding two images of a given moment could be identified starting from the image indicating the hand held object falling.

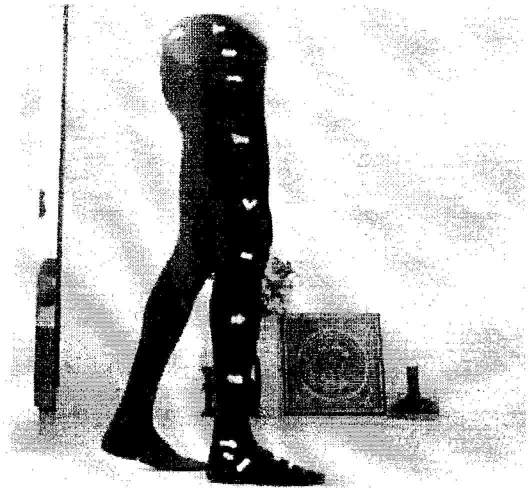

Fig 5.4: Subject walking

5.2 Data Analysis

The data obtained from the data capture are,

1) Images taken from both cameras at a time keeping the checkerboard at different positions - for camera calibration
2) Images of iron rod with markers on it taken from both cameras at a time – to calibrate the 3D space in which the subject was allowed to walk
3) Clips taken from two cameras of the walking subject – these clips were converted to synchronized image sets (dual) with 20mS sampling rate by using a motion to picture software (freeware). - These are the raw data to be analysed.

From the above data it was required to get the 3D coordinates of each marker placed on the leg of the subject with respect to a reference coordinate frame.

5.2.1 Individual camera calibration

Different types of camera calibration software have been developed by personnel involved in research activities in this field [17], [18], [19], [21].
Camera calibration toolbox is used for this purpose in Matlab. Toolbox is freely downloadable from http://www.vision.caltech.edu
The cameras were calibrated using the images of the planer checkerboard taken at different orientations. After corner extraction and calibration the individual camera parameters were saved in Matlab. Fig 5.5 shows all the images taken from one camera for calibration.

$$KK = \begin{bmatrix} fc(1) & alpha\_c * fc(1) & cc(1) \\ 0 & fc(2) & cc(2) \\ 0 & 0 & 1 \end{bmatrix} \quad (5.1)$$

$fc(1)$ and $fc(2)$ are the focal distances (a unique value in mm) expressed in units of horizontal and vertical pixels. Both components of the vector fc are usually very similar.

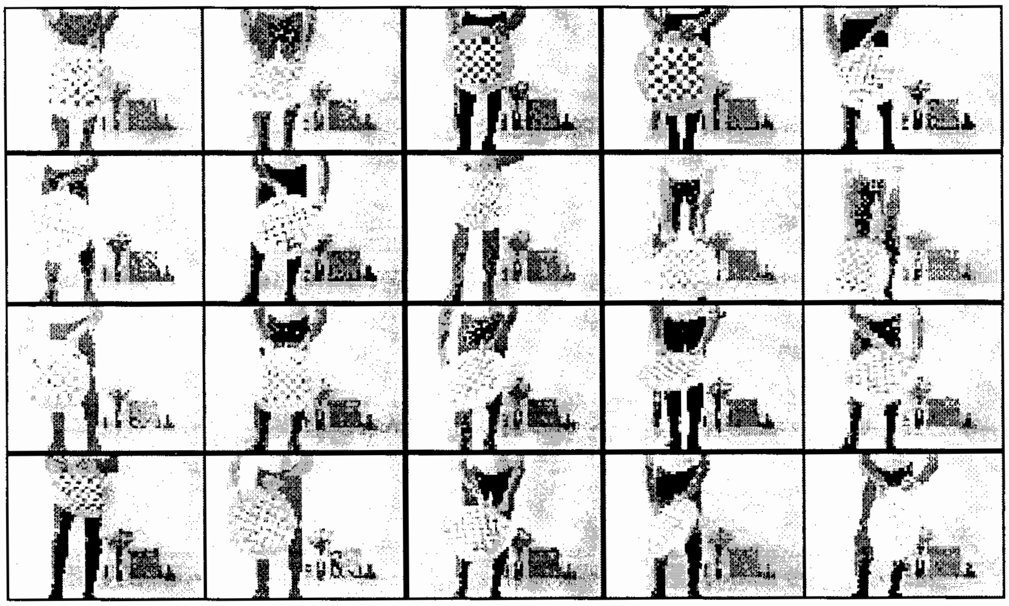

Fig 5.5: Calibration images using Matlab toolbox for camera calibration

The coefficient *alpha_c* encodes the angle between the x and y sensor axes.
In addition to computing estimates for intrinsic parameters, *fc, cc and alpha_c*, the toolbox also returns estimates of the uncertainties on those parameters [16].

5.2.2 Stereo camera calibration

After individual camera calibration results were saved in Matlab, stereo calibration of the two camera system was performed.
Results of the stereo camera calibration are the intrinsic parameters of the left and right cameras and Rotation vector (om) and Translation vector (T) [16]. Given below are the results arrived at after stereo calibration.

Following codes were generated after calibrating individual cameras and after running stereo camera calibration in Matlab.

Intrinsic parameters of left camera:

Focal Length: fc_left = [702.09311 703.44209] ± [22.01057 22.55728]

Principal point: cc_left = [354.47879 265.99827] ± [15.46725 10.58995]

Skew: alpha_c_left = [0.00000] ± [0.00000] => angle of pixel axes = 90.00000 ± 0.0 deg

Distortion: kc_left = [-0.19545 0.52156 0.00098 0.00045 0.00000] ± [0.04643 0.16253 0.00353 0.00667 0.00000]

Intrinsic parameters of right camera:

Focal Length: fc_right = [711.62122 700.62694] ± [34.31793 34.06319]

Principal point: cc_right = [263.47144 238.14992] ± [21.17618 13.85938]

Skew: alpha_c_right = [0.00000] ± [0.00000] => angle of pixel axes = 90.00000 ± 0.0 deg

Distortion: kc_right = [0.03456 -0.18577 0.00441 -0.02036 0.00000] ± [0.06859 0.13765 0.00453 0.01325 0.00000]

Extrinsic parameters (position of right camera wrt left camera):

Rotation vector: om = [0.00333 0.08814 -0.00716]

Translation vector: T = [470.68302 1.62464 66.34908]

5.3 Results after Calibrating the System

Matlab Symbol	Vector Size	Description		Value
Intrinsic Parameters				
Left Camera				
fc	2 x 1	Focal length in pixels	expressed in units of hirizontal pixels	702.09
			expressed in units of vertical pixels	703.44
cc	2 x 1	Principal point	horizontal direction	354.47
			vertical direction	265.98
anpha_c	Scalar	Skew coefficient	angle between x and y pixel axes	0
Kc	5 x 1	Distortion coefficient	radial and tangential distortions	-0.1954
				0.52156
				0.00098
				0.00045
				0

Table 5.1: Intrinsic parameters of left camera

Matlab Symbol	Vector Size	Description		Value
Intrinsic Parameters				
Right Camera				
fc	2 x 1	Focal length in pixels	expressed in units of hirizontal pixels	711.62
			expressed in units of vertical pixels	700.62
cc	2 x 1	Principal point	horizontal direction	263.47
			vertical direction	238.14
anpha_c	Scalar	Skew coefficient	angle between x and y pixel axes	0
Kc	5 x 1	Distortion coefficient	radial and tangential distortions	0.03456
				-0.18577
				0.00441
				-0.02036
				0
Extrinsic Parameters (position of right camera wrt left camera)				
om	3 x 1	Rotation Vector	expressed in units of hirizontal pixels	0.00333
				0.08814
				-0.00716
T	3 x 1	Translation Vector	horizontal direction	470.68
				1.6246
				66.3490

Table 5.2: Intrinsic parameters of right camera and extrinsic parameters

5.4 Stereo Triangulation

To find out the 3D spatial coordinates of the marks first it was required to identify the image coordinates of individual mark in pixels. Pixel coordinates are defined such that [0;0] is the centre of the upper left pixel of the image. Pixel coordinates of each mark was identified by clicking on the mark after opening the image in Matlab.

To get the 3D spatial coordinates of point in pixel coordinates, stereo triangulation was used in Matlab.

Following codes were generated in Matlab as description of the stereo triangulation function.

```
[XL,XR] =
stereo_triangulation(xL,xR,om,T,fc_left,cc_left,kc_left,alpha_c_left,fc_right,cc_right,kc_right,alpha_c_right).

Function that computes the position of a set on N points given the left and right image projections.
The cameras are assumed to be calibrated, intrinsically, and extrinsically.
Input:
    xL: 2xN matrix of pixel coordinates in the left image
    xR: 2xN matrix of pixel coordinates in the right image
    om,T: rotation vector and translation vector between right and left cameras (output of stereo calibration)
    fc_left,cc_left,...: intrinsic parameters of the left camera (output of stereo calibration)
    fc_right,cc_right,...: intrinsic parameters of the right camera (output of stereo calibration)
Output:
    XL: 3xN matrix of coordinates of the points in the left camera reference frame
    XR: 3xN matrix of coordinates of the points in the right camera reference frame
```


From the tabulated data of 2D pixel coordinated, 3D spatial coordinates were obtained by performing stereo triangulation. Similarly this was performed for the images of iron rod to calibrate the 3D space in which the subject was allowed to walk.

Chapter 6

Validation of the Apparatus for Human Motion Capturing

The 3D spatial coordinates were extracted from image data and the analysis is presented in a separate research project. Discussion in this chapter is on how accurate the implemented data capture mechanism in this work. The motion capture is primarily on the sagittal plane of the leg where most of the movement takes place.

Gait pattern result obtained using the proposed method was compared with much more accurate information on gait pattern. This 'real' gait data have been collected at Denver Children's Hospital, using the Vicon system. The multimedia presentation was prepared using the powerful 'Vicon Polygon' program [2]. Fig 6.1 shows the appearance of the polygon viewer software containing three panes skeleton movement, actual subject movement and graphics panes [22].

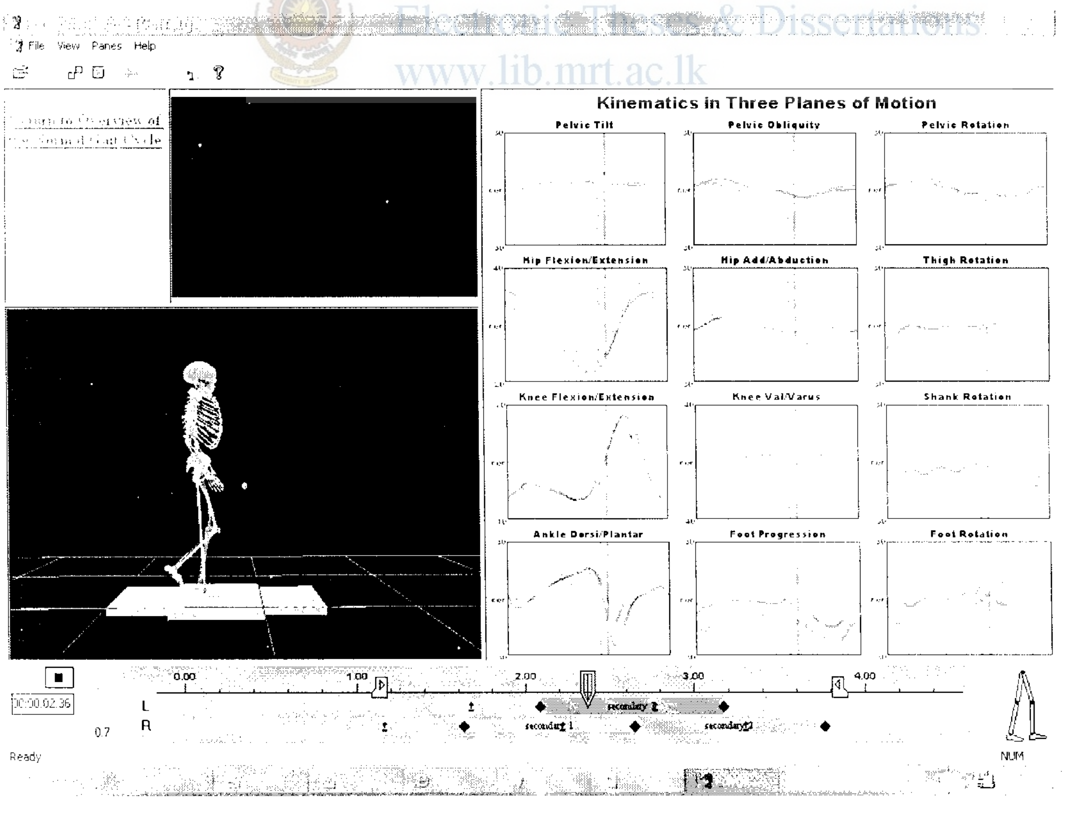

Fig 6.1: More accurate gait cycle information

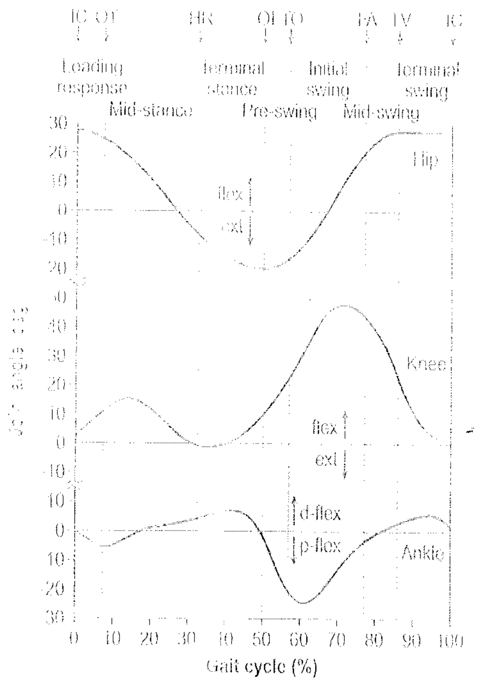

Fig 6.2: Published information on gait pattern (Source: Gait Analysis an Introduction by Michael W. Whittle)

Fig 6.2 shows variation of sagittal plane joint angles during a single gait cycle of right hip, knee and ankle. The subject used in obtaining this gait cycle information is a 22 year old normal female, weight 540 N, walking barefoot with a cycle time of 0.88 s, a stride length of 1.50 m and a speed of 1.70 m/s. The individual measurements from this subject do not always correspond to 'average' values, because of the normal variability between individuals, although they are all close to the normal range.

It is important to investigate how the measured joint angles are defined in the two scenarios before the comparison.

Joint Angle	Gait Pattern Obtained from Proposed Method	Gait Pattern Obtained from Published Source
Hip	Angle between vertical and femur	Angle between pelvis and femur
Knee	Angle between vertical and tibia	Angle between femur and the tibia
Ankle	90 deg minus angle between tibia and vertical	Angle between tibia and an arbitrary line in the foot for the walking (This angle is normally around 90 deg but taken as 0 deg)

Table 6.1: Definition of Measured Angles of the two methods

6.1 Data Comparison

A position of the leg during gait cycle is separately identified in biomechanics for the ease of analysis. Fig 6.3 indicates these leg positions.

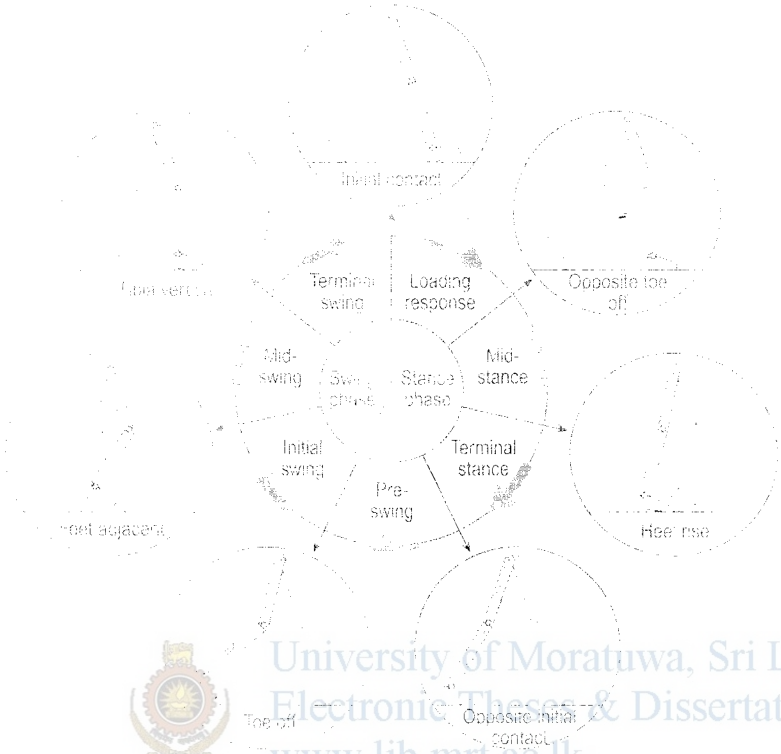

Fig 6.3: Positions of the legs during a single gait cycle by the right leg (Source: Gait Analysis by Introduction by Micheal W Whittle)

6.1.1 Hip Joint Variation

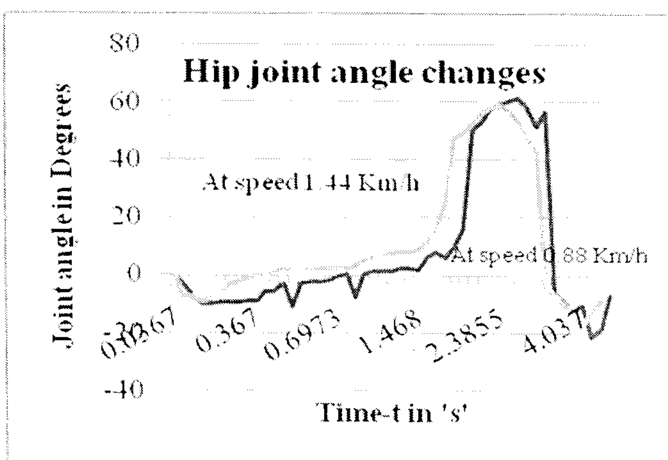

Fig 6.4: Hip joint angle variation

The hip flexes and extends once during the gait cycle, the limit of the flexion is reached around the middle of the swing phase and the hip is then kept flexed until the initial contact [2]. The pattern of the hip joint angle variation is very much similar to the cycle explained in [2]. The curve shows one extension and flexion during the gait cycle.

When magnitude of the hip angle variation of the two gait patterns is considered, it shows a significant difference. The maximum angle variation of the external source is about 48 deg, where as the actual obtained gait pattern show it to be around 80 deg. This is due to the definition of the hip angle is different in the two patterns.

Hip initially swings 60 degrees of swing phase until heel strike (HS), when hip begins extension until heel off (HO) and toe off (TO).

6.1.2 Knee Joint Variation

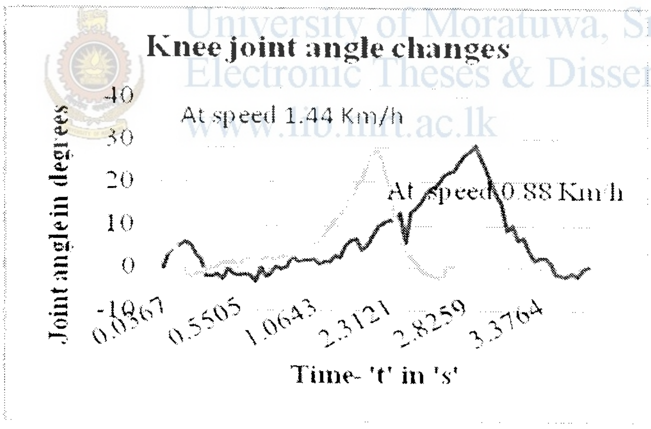

Fig 6.5: Knee joint angel variation

The knee shows two flexion and two extension peaks during each gait cycle. It is more or less fully extended before initial contact, flexes during the loading response and the early part of mid-stance, extends again during the later part of mid-stance, then starts flexing again, reaching a peak during initial swing. [2]

In Fig 6.5 it is indicative that knee joint undergoes two flexion and two extension peaks during its gait cycle.

The magnitude of the maximum angle variation of the proposed system is about 30 deg whereas the published data indicates it to be around 45 deg. In this case also, two scenarios of angle definition have caused the difference. However, the angle of flexion or extension depends on various other parameters of the subject, like gender, stride length dimensions of the leg etc. The magnitude of flexion is variable, both from one individual to another and with the speed of walking, but it is commonly between 10 to 20 degrees. [2]

Chapter 7

Discussion & Conclusion

As per the validation of the results in Chapter 6, the methodology adopted is a feasible methodology for analysing the identified movements of the leg during gait. Other sophisticated motion capture methods are being used in other parts of the world that are much more accurate [22], [23]. Implementation of this camera system was initiated to provide data for another research project to analyse human gait information. Implementation of this camera system for this purpose was done in four stages. Firstly to study the biomechanics of human walking to get an idea of how the outcome should be. Secondly different types of data capture methods were studied and compared to select the options that can be implemented. Thirdly a study was conducted about the selected data capture technique. Final stage was the actual data capture.

7.1 Recommendations

This technique explained in this research for capturing of human gait is a viable approach for human gait cycle analysis. The joint angle variation pattern obtained using this method is inline with the published information.

Through this project it was identified that this technology can be used in other fields of studies as well. Stereo vision used in machine vision and robotics is based on similar studies. Camera based techniques are widely used in 3D reconstruction in film industry. Also in smart surveillance systems

7.2 Limitations of the Study

The magnitudes of the joint angle variations have shown some deviations from the published information due to the difference in joint angle definition. The methodology is highly labour intensive and time consuming.

7.3 Suggested future work

Following areas were identified that need to be improved in this motion capture method.

1) In this study, the captured motion information was in the form of digital clips taken from two Webcams. These digital clips were later translated to digital images using a motion to picture software. This process proved to be accurate enough to give a good outcome. The data capture method can be improved in this respect by using a triggering mechanism provided that enough bandwidth as allowed for the data capture equipment to save the image data.

2) The extraction of pixel data from the image was done by clicking on each marker on the image in Matlab. This process is very likely to have human errors. For this purpose image segmentation can be done to extract the markers through a software application.

3) In this work the noise introduced in data capture method have propagated to the next level of analysis. Use of motion data filtering technique could further improve the output.

7.4 Practical problems faced during the implementation

The major problem faced during the implementation of this motion capture system is that finding the correct apparatus for the work.

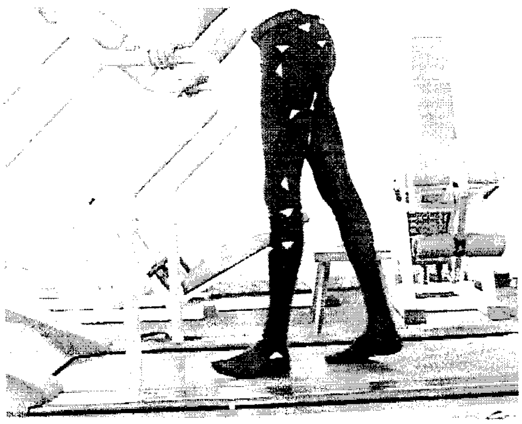

Fig 7.1: Motion capture from video cameras

The motion capture had to be performed several times to get images of good value for the research work. The first motion capture apparatus that was tried out was the video camera based motion capture. The data capture was performed while subject was walking on a treadmill. Fig 7.1 shows a captured image during the motion capture.

In this method video clips were converted to images using video editing software and again converted to digital form that is jpeg or bitmap form. Due to the ill effect of the jpeg or bitmap images the images could not be processed further. When camera calibration engine was run, with a set of images, result generated ill effects.

Motion capture through the proposed method was also had to be done several times to obtain images that can be processed further for this study.

References

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