CHAPTER 3

DEVELOPMENT OF ACTIVE MARKER BASED CAMERA MOTION GAIT ANALYSIS SYSTEM

3.1 Camera Motion Gait Analysis System

Accurate measurement of human motion parameters is prerequisite for gait analysis inferences. Camera Motion gait analysis system is used to describe the process of recording movement and translating that movement onto a digital model for gait spatiotemporal parameter measurement. The quality of information is highly dependent on the type of camera motion system used. It is therefore, important to have in-depth discussion about the prevailing camera motion analysis based techniques for gait analysis. The very first gait motion measurement tool are human eyes, which has serious limitation of being individualistic and thus not reliable. Also normal gait is rapid (approx. 105 steps per minute) and the human eye is not fast enough to clearly separate the various components of gait at this speed. Camera motion system is the best substitute which may be easily employed for gait analysis. As discussed in chapter 1, kinematic systems are broadly divided into contact based (direct measurement) and non-contact based (imaging) technique. Direct measurement devices suffer from severe measurement limitations in terms of instrumental errors. To overcome the limitation of contact based kinematics, researchers started image acquisition modalities (video and marker) for kinematic image assessments. Video based method uses video image environment in which there is lot of data processing of unwanted information and analysis is done manually which is labor intensive. To overcome drawbacks of video based gait, scientists employed markers. Markers are attached near to each joint to identify the motion by the positions or angles between the markers. Broadly Active (light emitting) and passive (retro-reflective) marker or combinations of any of these, are tracked, optimally at least two times the frequency rate of the desired motion, to decipher sub millimetre positions. Active markers use LEDs to generate image information. Passive markers are spheres covered with retro-reflective Scotchlite tape. The tape is specifically designed to reflect incident light directly back along its line of incidence.
These optical gait measurement systems utilise the data captured from image sensors embedded with markers to generate the 3D position of a subject between one or more cameras calibrated to provide overlapping projections \(^{146}\). The image data is analysed manually and each marker attached to a limb segment is tracked down. Image background plays an important role and therefore, gait analysis labs generally have nearly complete dark environment for image capture. Later on, software tools have been evolved to generate automatic and accurate data by tracking these markers dynamically for each particular subject. For tracking a large walkway, the capture area is equipped with the addition of more cameras. These systems produce data with three degrees of freedom for each marker and rotational information must be inferred from the relative orientation of three or more markers; for instance hip, knee and ankle markers providing the angle of the knee \(^{147}\).

### 3.1.1 Passive Marker Systems

These systems use markers coated with a retro-reflective material to reflect light back that is generated near the cameras lens (Fig. 3.1a). As they reflect the incident light, they don’t require any source of energy to power the marker and thus, there is no fuss of wires hanging around the body as in the case of active markers. The camera’s gain is adjusted so that only the bright reflective markers are sampled, ignoring skin and fabric (Fig 3.1b). The centroid of the marker is estimated as a position within the 2-dimensional images that is captured. Calibration is done with specialized devices called wand (statically and dynamically) which obtains camera position and lens distortion of each camera. Such system consists of around 6 to 24 cameras. More number of cameras is required to eliminate swapping of markers. Passive marker system can capture large numbers of markers at frame rates as high as 2000fps. Strobes of different wavelength are used in order to have the maximum useful information. For example, Infra-red flash illuminators surround each camera lens sending out pulses of infra-red light that are reflected back into the lens from the marker (Fig 3.1c).
3.1.2 Active Marker Systems

The first active markers used were light bulbs located at hip, knee and ankle. Later on, active markers used light emitting diodes (LEDs) which can be attached to subject’s anatomical landmarks and there is cable attached to it for power transfer. The uniqueness of this system is that only one LED illuminates (Fig. 3.2a) with some predefined high sampling rate which gives only one LED per frame in image. The LED glowing frame rate is synchronized with camera capture rate (Fig. 3.2b). The ability to identify each marker in this manner is useful in real-time applications. The disadvantage of this technique is after sampling the first marker, it must sample all other markers before it can sample the first marker again. This means the sample rate reduces as the number of markers increases. The sequential pulsing of active marker system ensures that marker occlusion and ghosting are not an issue and, in turn, unlike passive markers, active markers can be placed close together. Unlike passive markers, the active markers themselves are powered to emit their own light.
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As both the optical systems use two different technologies, a comparison is given in Table 3.1. Both marker systems have their own advantages and disadvantages. Based on the situation, a wise choice of the system is made.

Table 3.1: Comparison between Active and Passive markers

<table>
<thead>
<tr>
<th>Active Markers</th>
<th>Passive Markers</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ These are active devices like LEDs, IR LEDs which emit light.</td>
<td>✓ These are passive sensors like reflective spheres, tapes etc</td>
</tr>
<tr>
<td>➢ They can have their own signatures for tracing any joint.</td>
<td>✓ These are passive by nature and do not have any signature associated</td>
</tr>
<tr>
<td>➢ Easy setup and calibration</td>
<td>✓ Setup and calibration complex</td>
</tr>
<tr>
<td>➢ Cost effective.</td>
<td>✓ Costly</td>
</tr>
<tr>
<td>➢ More equipment carried by the subject like cables, battery.</td>
<td>✓ No cables and backpack required.</td>
</tr>
</tbody>
</table>

3.2 Kinematics for Prosthetic Development & Quantification

Findings of gait analysis (kinematics and kinetics) can be applied to the process of prosthetic design, performance evaluation and to improve functionality. The prime application of gait prosthetic has evolved after World War II to evaluate rate of rehabilitation of soldiers. Later on, when development of electronic knee started, the control parameter and ranges were generated with gait analysis. Kinematic parameters generate optimal pattern of gait which is used as design input. Temporal and kinematic data is recorded at slow, normal and fast speeds and these help to generate knowledgebase for Above-Knee prosthetics. The parameters like stance duration, heel strike and toe off phase and knee flexion angle have been identified as control parameters and their ranges are programmed into microcontroller. These spatio-temporal measurements can also
be done with direct measurement technique with some limitations. Kinematics identifies symmetry of gait in amputees and the literature suggests that amputees demonstrate asymmetrical gait patterns. These dynamic motion studies are critical to the full assessment of the injury, recovery and subsequent rehabilitation\cite{38}.

Observational analysis is only moderately reliable technique for prosthetic performance assessment. It is very predominantly used in India. Based on the responses received to questionnaire method for patient comfort, indigenous prosthetic devices are graded\cite{40}. There are no evidences for scalable and quantified parameters of performance for prosthetic devices used by larger strata of society. The quality and performance is limited to the specification of the devices-imported or indigenous.

Constantly newer and improved versions of knee are being designed and manufactured in developed countries. With progressing technologies and real like simulation, prosthetic devices may be evaluated and graded in a scientific manner. The prosthetic knee is divided into three links for a biomechanical analysis, a link between upper body and hip, second link at hip and knee and third link at ankle joint. The areas in which knee performance is judged are proper alignment and the correct spatial relationship between artificial socket and the natural limb as these features are paramount to attain an efficient, comfortable gait with a desired loading pattern on the residual leg. There is not standard data base available for quantification of the prosthesis of an amputee; it is done by comparing its gait parameters with that of his healthy limb. Inspite of having advanced prosthetic designs, the fitting and alignment of device remains subjective and nonsystematic due to the very high input cost in setting up a gait lab. As a result, in India, only 3-4 labs are established and none of them is working in prosthetic biomechanics. Therefore, there is an urgent need for a reliable and cost effective motion capture system.

Looking at the importance of camera based gait analysis, we took a challenge to develop an active marker based camera motion gait analysis system.
3.3 Design of Active marker based Gait Measurement System

Gait parameters kinematic and kinetics are measured for identifying gait disorders. Kinematics is the science of studying human dynamics. In kinematics, instrumentation is required to estimate positions, angles, velocities and accelerations of body segments and joints during motion. Accurate estimation of human kinematics requires interdisciplinary domain knowledge of biomedical engineering, biomechanics, mechatronics, and human anatomy sciences. For kinematic assessment, camera motion gait measurement systems are preferred over visual observation method as the later has several limitations and inaccuracies. Gait measurement (GM) system is used to have spatiotemporal parameters such as gait speed, stride length and cadence. Literature reports that footstep measurement system which uses chalk and inkipad methods has the advantage of generating accurate data on step length and step width, but it is cumbersome and time consuming. The movement parameters are synchronized with the kinetic parameters (body forces) to generate quantitative description of gait or human dynamics in the form of time-distance parameters and variations in joint angles, joint moments and joint powers.

After understanding both the techniques, we have generated a hybrid approach, where we have developed red LED based marker and applied them to lower muscle joint; hip, knee and ankle. We have used 1.3 Mega pixel cameras with a frame rate up to 50 fps. Usage of active markers in a video based environment being simple and cost effective, brings out the advantages of both technologies. Also we have not used any kind of pulsating circuitry which is there in commercially available active marker system. In case of marker based gait analysis techniques, manual analysis of these marker images is error prone, labor intensive and a tiresome process. This motivated us to develop an automated software algorithm that would analyze spatio-temporal features of human gait kinematics. The acquired image data was processed and analyzed using LabVIEW Vision for determination of spatio-temporal parameters like knee flexion angle, its range, joint trajectory tracking, stride length, stride time, stance time, swing time, stride velocity, cadence and vertical displacement. Experimenting with these parameters, we have gained an understanding about how to use them as starting design input and for device performance quantification. This as well gave us the confidence to, develop an
indigenous gait measurement system which is automated, easy to use, cost-effective, and provides detailed quantitative information, causing minimum discomfort to patients\textsuperscript{[66, 67, 68]}. The development is divided into image acquisition hardware (camera + LED based Active markers) and the software algorithm for generation of kinematic and spatio-temporal parameters written in LabVIEW Vision.

### 3.3.1 Image Data Acquisition Setup

#### 3.3.1.1 Active markers

We have used available red colour conventional LEDs, with each marker made up of an array of four LEDs (Fig. 3.3a) arranged in such a fashion that they appear as a big and single bright circle when viewed from some distance through camera. A microcontroller (AT89C52) based marker pulsing unit is also designed and implemented. It is found that static glowing LED markers served the purpose and the algorithm developed did not necessitate blinking of LED’s, hence the pulsing circuitry is not used. This also gives newness in using the active markers in video based environment. The synchronization of camera frame and LED is also not required. Later on to make the marker system more compact so that markers can be applied at smaller anatomical landmarks, normal LED’s were replaced by single high intensity Philips red LED markers (Fig. 3.3b).

![Fig. 3.3: a) Active marker using conventional LED b) Active marker using LUMILEDS](image)

These markers are fixed on to the anatomical landmarks i.e. hip, knee and ankle for lower limb analysis using both-sided adhesive tapes for gait measurement experiment as depicted in Fig. 3.4a. Figure 3.4b shows the successful application of in-house developed active marker for full body gait analysis.
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![Active marker for lower limb analysis using conventional LED](a)  ![Active marker for full body analysis using Lumileds](b)

**Fig. 3.4:**

**3.3.1.2 Camera Setup**

For image acquisition of dynamic walk in the sagittal plane, a Lumenera LU120M series (Fig. 3.5a), 1.3 Mega pixel, USB-2 camera with an 8.5 mm lens is used. The images are acquired at a resolution of 640 x 480 at frame rate of 50 fps. Sequence acquisition mode is used to capture 225 frames for one walk. The acquired images are saved in National Instruments proprietary *.apd file format. Figure 3.5b shows the image acquisition block diagram for lower limb gait analysis.

![Lumenera USB Camera](a)  ![Block diagram for image acquisition setup](b)

**Fig. 3.5:**

One of the debatable questions was the length of capture walkway and we decided it to be 15 ft after analyzing the fact that it can over 3-4 strides of gait which is sufficient for our application of lower limb analysis. Camera is mounted on a stand at a height of 4 ft so all marker attached from toe to hip can be covered in the frame. The total captured imaging volume is 16 ft³ as shown in Fig. 3.6. Image acquisition is done in complete black background for better image...
contrast ratio. For the required application it is found that camera (640 x 480, 50 fps) is reasonably good. The frame rate of 50 fps is high frame rate to capture different speed walking trials.

The selection of camera resolution (higher the better) and capture frame rate (higher the better) are challenging tasks. A tradeoff is required between resolution and capture frame rate as these are directly proportional to the camera cost. Camera compatibility with computer hardware in terms of driver software is another issue to look into. We have selected Luminera camera for which LabVIEW driver support is available. Figure 3.7 explains the software algorithm for image acquisition.

![Flowchart for Image acquisition](image)

**3.3.2 Software Algorithm for Kinematic measurement**

Software algorithm is written for tracking of markers and reporting the spatiotemporal parameters values from the gait of subject. The first step is to make the acquired images compatible to the vision development system. The acquired images are 32 bit images (Fig. 3.8a) which are preprocessed to 8 bit. For pattern matching, template of marker is required which helps to locate the markers in images. A marker template was created as shown in Fig. 3.8b which acts as a reference. In a template, a grayscale image has intensity values that correspond to the plane extracted using the color plane extraction function (the extracted plane being Red here).
The software flow for kinematic measurement, depicted in Fig. 3.9, is divided into initial function selection and separate function for each spatiotemporal parameter is dealt separately.
3.3.2.1 Flexion Angle Determination Function

The prime important function in developed software algorithm (Fig. 3.10a) - the tracking of markers - includes pattern matching based on intensity measurement. From the main algorithm, all measurement functions are divided into smaller subroutines, but all have one step common that is identification of markers (their location coordinate). The intensity (score) of marker varies depending on the camera-marker orientation and background environment. A minimum score is defined which specifies the minimum grade an instance of the template can have to be considered a valid match. We have defined a minimum score of 750 as a matching threshold. This value is assigned to discard the chance of any other reflective object to be considered for analysis. As we have fixed the marker at hip, knee and ankle so the number of markers to be traced is 3, and low number of markers is advantageous. The software determines the number of matched patterns along with their X-center, Y-center and the score of each valid match as shown in Fig. 3.10b.

The angle between the three markers can be determined, provided their center coordinates are known. From the pattern matching results, we obtain the Y-coordinates of the detected markers. The markers are then identified as M1, M2, and M3 in ascending order of their Y coordinate values. The marker with lowest Y coordinate value is graded M1. Similarly M2 and M3 are determined using their Y coordinate values. The angle between the markers M1, M2 and M3 is determined as shown in Fig. 3.10(c). The Knee flexion angle is then calculated using the equation 3.1:

\[
\text{Knee Flexion Angle} = \{180^\circ - (\text{Angle M1M2M3})\}
\]  

(3.1)
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Fig. 3.10 (a) Software algorithm for flexion angle determination function (b) Marker Pattern matching (c) Caliper function for angle determination
3.3.2.2 Trajectory Tracking of Joint Movement Function

Figure 3.11 explains the trajectory tracking function for lower limb joint movements. The trajectory of hip, knee and ankle joints is tracked through acquired frames. The coordinate values of each marker in each acquired frame are stored for calculating the joint movement function. The importance of trajectory tracking gives the displacement in marker position in the x-y plane. A defined marker template is created similar to that of angle determination function. For each of the three markers, we define a region of interest (ROI) in the frame through which the marker is most likely to traverse when the subject is walking as shown in Fig. 3.12a. When the markers in all the images are detected, we get the (x, y) coordinates as illustrated in Fig. 3.12b. The (x, y) coordinates of the three markers at separate locations are stored and further used for calculating gait parameters.

Fig. 3.11: Flow Diagram for trajectory tracking
The (x, y) coordinates of each marker give its spatial position in current frame. Coordinate values for each frame acquired, are plotted to get the trajectory of particular joint motion. With the known values of frame rate, imaging volume in terms of walkway distance and total number of frames contributed for one gait cycle, all of the kinematic parameters are calculated. This is very important function from the point of view of the accuracy of the software tool.

3.3.2.3 Stride Length Function

Stride length is basically the distance between two successive placements of the same foot. In the trajectory function, the coordinate values of ankle marker are stored and are used for determining the stride length. Software tool calculates the distance between two successive minima’s of the ankle marker trajectory for determination of the stride length from the imaging data as shown in Fig. 3.13. To find the stride length, equation 3.2, we have to determine the difference between the X co-ordinates of $Y_{\text{min}2}$ and $Y_{\text{min}1}$, i.e. $X_{\text{min}2}$ and $X_{\text{min}1}$ respectively

$$\text{Stride Length} = X_{\text{min}2} - X_{\text{min}1}$$  \hspace{1cm} (3.2)

For stride length calculation, the total width of the frame (640 pixels) represents approximately 15 ft of the walk way.
3.3.2.4 Stride Time Function

This function calculates the Stride time using the data available for frame rate and total walkway distance in the field of view (FoV) of the camera. In our case, the total number of images with all the markers visible in the frame is 225. With the frame rate of 50fps, the time to cover full walk in the frame of 64 pixels is 4.5sec. Stride time can be calculated using the available data of total distance covered in the frame and the time taken to cover this distance. Stance phase and swing phase comprise 60% and 40% of the total gait cycle respectively. Thus stance and swing time can also be calculated.
3.3.2.5 Stride Velocity Function

From the available data of stride length and stride time, stride velocity can easily be calculated as given in equation 3.3:

$$\text{Stride velocity} = \frac{\text{Stride length}}{\text{Stride time}}$$

(3.3)

3.3.2.6 Cadence Function

Cadence is the number of steps taken in a given time and it is measured in steps per minute. Step length is half of stride length. We have already calculated stride length and stride time values, thus cadence can be derived.

3.3.2.7 Vertical Displacement Function

This software function (Fig. 3.14) calculates the vertical displacement of individual anatomical landmark. Any hopping in the gait of patient is related to abnormalities. It is the range of variation in vertical position of the individual during a walk cycle. For example, the hip displacement can be assumed to represent the range of height covered by the individual during the walk as the upper torso is almost constant in height when compared to the lower half. The range of vertical displacement is determined by calculating the difference between $Y_{\text{max}}$ and $Y_{\text{min}}$ in each frame from the data obtained for the trajectory traced by the hip joint.

![Flowchart for vertical displacement function](image-url)
3.4. Results

Experiments were carried out on normal healthy individuals with their consent. They were asked to walk at self-selected speeds - slow normal and fast. Multiple trials of their walk were acquired using the indigenously developed active marker camera system. Huge amount of image data was stored in a separate drive. The developed software algorithm is applied on the image data for determination of the various spatio-temporal parameters. Using flexion angle determination function, knee flexion angle was determined. The knee flexion angle with respect to time for one gait cycle is plotted in Fig. 3.15. The knee flexion angle is observed to be varying from a minimum of 7° to a maximum of 54° indicating a knee flexion range of about 47°. The results obtained are in accordance with the normal knee flexion values reported in literature by other methods. The accuracy of result obtained from this software tool is verified by experimentation for knee flexion determination using electro-goniometers. The results from both the techniques were comparable.

Fig. 3.15: Knee-Flexion Angle for one gait cycle
All the calculated spatio-temporal parameters for normal walk of healthy individual are reported in Table 3.2.

Table 3.2: Spatio-temporal parameters using developed GM system

<table>
<thead>
<tr>
<th>Gait Parameter</th>
<th>Calculated Values by developed GM system</th>
<th>Normal Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Flexion Angle Range</td>
<td>47°</td>
<td>45°-60°</td>
</tr>
<tr>
<td>Stride Length</td>
<td>1.58m</td>
<td>1.33 to 1.63 m</td>
</tr>
<tr>
<td>Stride Time</td>
<td>1.56 sec</td>
<td>1.0 to 1.12 sec</td>
</tr>
<tr>
<td>Swing Time</td>
<td>0.62sec</td>
<td>0.39 to 0.40 sec</td>
</tr>
<tr>
<td>Stance Time</td>
<td>0.93sec</td>
<td>0.63 to 0.67 sec</td>
</tr>
<tr>
<td>Stride Velocity</td>
<td>1m/sec</td>
<td>0.82 to 1.60 m/sec</td>
</tr>
<tr>
<td>Cadence</td>
<td>77 steps/min</td>
<td>100 to 131 steps/minute</td>
</tr>
<tr>
<td>Vertical Displacement</td>
<td>0.011m</td>
<td>---</td>
</tr>
</tbody>
</table>

Image data of individual walk is analysed after applying Trajectory Tracking of Joint Movement Function. Figures 3.16, 3.17 and 3.18 depict the joint trajectory movement for hip, knee and ankle joint respectively. The rest of the parameter values are derived by applying other software functions on these stored coordinate values with known frame rate and imaging volume.
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Fig. 3.16: Trajectory movement of Hip

Fig. 3.17: Trajectory movement of Knee
3.5. Conclusions

A low cost and effective scheme for spatiotemporal parameters measurement using active marker camera motion system is successfully demonstrated. The development is based on the unique concept of utilizing the active markers in video based environment without any fast switching of camera equipment or LED based marker system. The gait measurement system is achieved with conventional LED’s and off-the-shelf available monochrome camera. Software codes are written on LabVIEW Vision platform. The software algorithm is based on advanced digital image processing techniques for kinematic analysis of human gait. The algorithm uses various functions like pattern matching, caliper, angle measurement functions etc of image processing for determining spatio-temporal parameters of human gait. Algorithm calculates the value of eight important gait spatiotemporal parameters. All the parameter values calculated by developed software tool are rechecked with the conventional methods of direct gait measurement, i.e. through electrogoniometers. Little variation was found in the measured value but it is within acceptable limits. The system accuracy is satisfactory in view of available components.
limitations of camera frame rate and resolution. Later on, this concept may also be extended for full body kinematic analysis or for specifically upper limb motion analysis with little or no changes. Walking is comparatively a slow activity; for analyzing full body gait, which is a faster activity, a camera with better frame rate and resolution is required.

The present method of camera motion analysis can be applied to any application of biomechanics like, for the assessment of deviation in normal walk due to neurological disorder. The experiment done gives us a range of gait parameters which can be applied for prosthetic design. Parameters like knee flexion angle and swing and stance duration are found to be extremely useful for design of a prosthetic knee. With the system measuring the gait parameters with accuracy, it is very useful in quantifying the performance of developed device or it may be used in standalone mode for assessment of performance of any device.