Invited paper

DEVELOPMENT OF AFFORDABLE OPTICAL BASED GAIT ANALYSIS SYSTEMS

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Abstract

This paper presents a review on the development of affordable optical based gait analysis systems at Institut Teknologi Bandung. The development started with a 2D inverse dynamic analysis of human gait using five linkages based on an experimental motion data. Using a simple system consist of a camera, LED markers and a PC, the position of the markers were obtained by capturing and processing digital images of markers attached to human body during motion. The marker positions data was then used for further kinematics and dynamic analyses. An in-house kinematic and kinetic software has been developed for this purpose. From the analyses, the spatiotemporal gait parameters such as stride-length, cadence, cycle-time, speed and joint angles can be obtained as well as forces and moments. In the second stage, the 2-D analysis was improved by using seven linkages to include the foot. Using this, the system has been able to analyze ankle angle, position of the centre of pressure and ground reaction force distribution. Currently, the development is continued further for a 3D dynamic analysis of human gait using two cameras and a PC. As an outcome of this development, a database of Indonesian normal gait was established. This result is the first data available for gait of Indonesian. It is hoped that the quantitative data provided by this system can help physicians to diagnose and plan the treatment for patients.

Keywords: Digital image processing, Gait analysis, Inverse dynamics, Multibody system

Introduction

Human motion has long been investigated for several applications, such as medical diagnostics, physical therapy, and sport science [1]-[5]. In the field of human motion study, optical-based motion analyzer systems have been widely used, most notably in gait analysis for medical rehabilitation purposes [5] where it can be used to monitor a patient's response during medical rehabilitation. Movement variables (such as step length, cycle time, stance-time and gait velocity) of a patient can be monitored and analyzed to indicate whether improvement or deterioration has taken place. These measures can also be compared against age- and sex-matched normal population distributions to determine whether the patient is approaching normal performance [6]-[8]. It is evident that the availability of quantitative gait parameters allows therapists to better understand a patient's gait pathology [9]-[13].

At present, many commercial camera-based motion capture systems for both 2D and 3D analyses are available. In such systems, the cameras send out infra red light signals and detect the reflection from the markers attached on the body. These systems are highly accurate, and often able to locate a marker to within 1 mm, having less than 1 mm of error [14].

However such benefits come at a price and may not be within the budget of most hospitals, especially in Indonesia.

As alternative to the above systems, more affordable quantitative methods based on video technology and personal computer are available such as ones reported in [15] – [16]. Even though important parameters could be obtained by this method, the process is quite time consuming and neither kinematic nor dynamic data such as joint angle, and working forces at joints and foot could be collected.

In order to overcome the lack of the system availability, a series of research on the development of affordable and integrated 2D and 3D optical motion analyzer systems has been conducted at the Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung (FMAE-ITB), Indonesia. The first development utilized a 25 fps home video recorder and a PC-based data acquisition system [17]. A set of LED markers were used to track the object. Later, a 90 fps camera was employed to improve accuracy [18], and the algorithm was further developed to overcome the occlusion problem of the markers [19]. The system is further improved by utilizing the Direct Linear Transformation (DLT) method in the calibration process. An inverse dynamic analysis software for kinematic and kinetic of the gait was also developed using five linkages multi-body system [20].The first prototype of the system has been able to provide a good quantitative spatio-temporal gait parameters as well as the joint angles, and also forces and moments.

In the second stage of development, the 2-D system has been improved to include foot data, which is very important so the system could provide additional gait parameters, i.e. ankle angle, position of the centre of pressure and ground reaction force distribution. In the second system, the optical motion capture system consists of two cameras to catch both left and right legs movements at the same time. A filter was attached to the lens so the experiment may be conducted in a normal natural light environment [21]. At this stage, a seven linkage multibody system was used for inverse dynamic analysis to obtain kinematic and kinetic of the gait [22]. The system has been tested, and in addition to the parameters obtained from the five linkage multibody system, this prototype provides ankle angle, position of the centre of pressure and ground reaction force [22].

Currently, using similar optical methodology, the system is further developed for a 3D gait analysis. Here, an optical motion-capture system is developed to detect and track the body segment movement in the form of markers position in 3D space [23]. The observational data obtained is then used for a 3D kinematics and kinetics analysis of human gait [24].

The developed five linkage 2-D system has been employed to determine 2D gait parameters of 60 subjects to initiate the development of Indonesian walking database [25] and was followed by another 212 subjects [26]. At the moment another study of Indonesian walking database using a seven linkage 2-D system is being carried out, and will be followed by a similar study using 3-D system.

In this paper, the development of affordable optical based gait analysis systems at FMAE-ITB that has been conducted up to now is presented. Most of the development milestones, starting from a simple optical based five linkage 2D motion analysis system up to a more complex 3D system are described here. Foregoing the details that could be found in references, image processing algorithms as well as kinematic and kinetic analyses are described and sample of gait data of Indonesians of various sexes and ages are provided.

Digital Image Recording and Processing

The First Stage of Development (2D Motion Capture System)

System Description

The gait cycle is the time interval between two successive occurrences of one of the repetitive events of walking. Starting from initial contact of the left foot, for example, followed by various events, the cycle continues until the left foot makes contact with the ground. The duration is known as cycle-time, consisting of stance-time and swing-time [1]. Usually, a motion analyzer system yields coordinate data of markers for evaluation of stride-length. Figure 1 depicts the stride length, defined as the distance between two positions of the same foot, consisting of right- and left-step lengths. Other important gait parameter is cadence, which is defined as the number of steps taken in a given time, and is inversely proportional to cycle time. The walking speed is evaluated based on the stride length and cadence. Further, other kinematic and kinetic data could also be obtained.

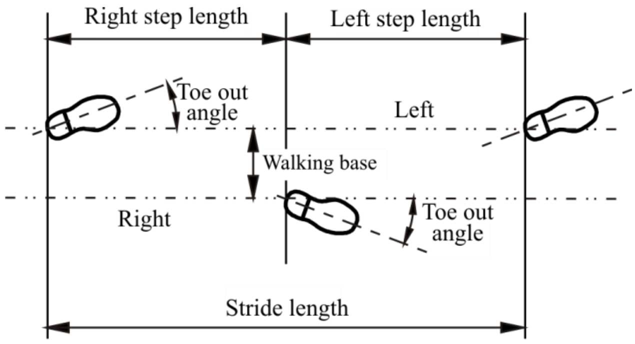


Figure 1. Stride-length

The first system developed for gait analysis at FMAE-ITB [17] is illustrated in Figure 2. In general, the system consists of both image recording and processing system [18], and a computer program for kinematic and dynamic analyses of human gait [20].

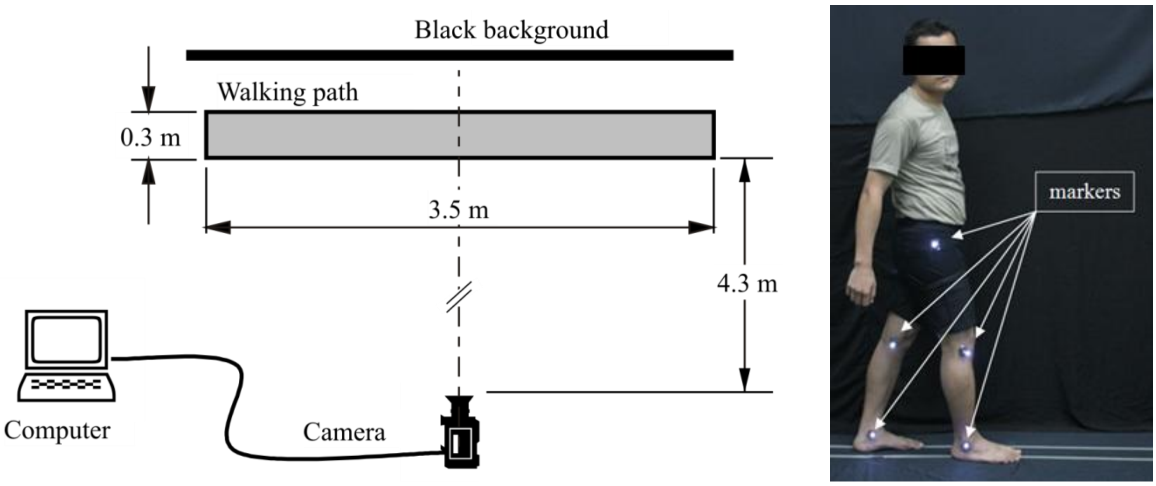


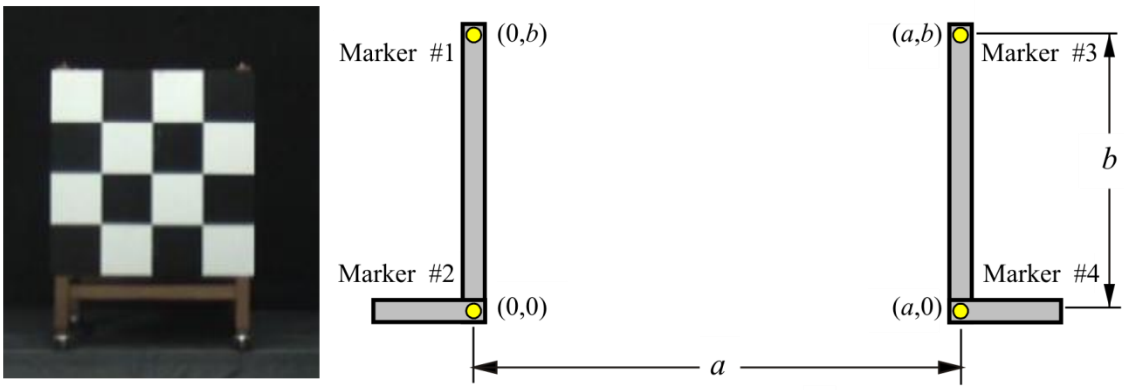
Figure 2. Description of the first 2D gait analysis system and marker positions

Five of eight-mm-diameter *LED* markers, as in Figure 2, were attached to anatomical landmarks, i.e. hip, both knees and ankles, on the subject and as the subject walked, the images were recorded using a home video camera which is placed orthogonally to the walking path. To obtain a good contrast, a black background was installed and the subject wears dark clothes.

Before recordings started, a calibration process was conducted using a calibration board having a chessboard pattern as shown in Figure 3(a). Due to limited resolution of the home video camera (720 × 576 pixel), the pattern size used in the first development was 15 x 15 cm2 for each square. From this process, correlation between length in pixel and in the real world coordinate may be obtained. Image from each frame was then processed, by conducting a detection, tracking and reconstruction to finally determine the coordinates of the markers as a function of time.

To acquire a finer and more accurate data, in the later development of the first stage, a 90 fps video camera replaced the home video camera. This 90 fps camera was then connected to an image acquisition card installed in the PC and utilized as a frame grabber to acquire video data captured.

The calibration process was also improved by using Direct Linear Transformation (DLT) technique [21], first developed by Abdel-Aziz and Karara [27], and also utilized by Kwon [28] for movement analysis. The DLT transform the coordinate of an object in the image plane into the real world coordinate. As shown in Figure 3(b), for this calibration purpose, image of a set of control markers was used, where the coordinate position of each marker in the real world coordinate was known. The DLT parameters could then be calculated based on the known real coordinate and image plane coordinates of the control markers. The calculated DLT parameters were then used after tracking process to transform the image plane coordinate of markers attached to the subject into the real world coordinate.



(a) (b)

Figure 3. Calibration process (a) chessboard pattern (b) DLT markers

Image Processing

The recorded video was detected and tracked in order to obtain the markers coordinate in the real world coordinate of each frame, as depicted in Figure 4. Prior to marker detection, the digital video data in RGB (Red, Green and Blue) format was converted into intensity format (grey scale), then into binary format, by introducing a threshold value. Every pixel having intensity below the threshold value was converted to black and everything above becomes white. After the thresholding process, the white markers representing hip, knee and ankle from the images could then be reliably extracted. The *xy* – coordinate of the markers were then calculated in the image plane (in pixels) on the basis of the marker's centroid.

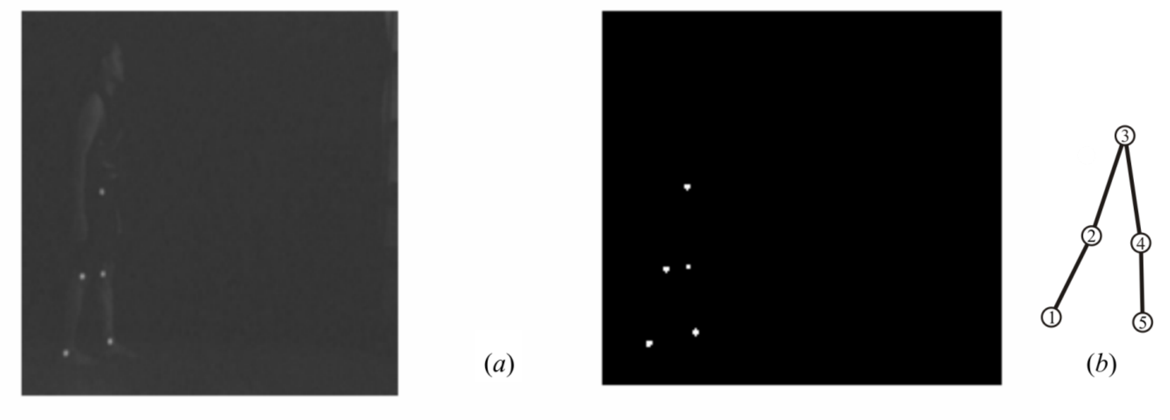


Figure 4. Marker detection scheme (a) image binarization, (b) marker number and position

At this point, the marker's positions in image plane have been identified. However, since the marker detection process began from the left to the right side of the image, the order of marker number in each frame is not always consistent. To solve this matter, a tracking procedure based on least distance method is employed. To track the marker's movement, the distance between the n^{th} markers in frame i+1 and frame i was calculated, and the marker's displacement was defined as the shortest distance between markers. This method is illustrated in Figure 5.

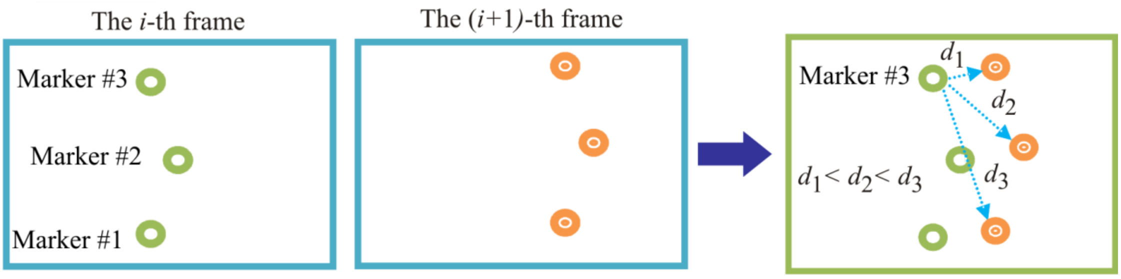


Figure 5. Tracking procedures of markers by least distance method

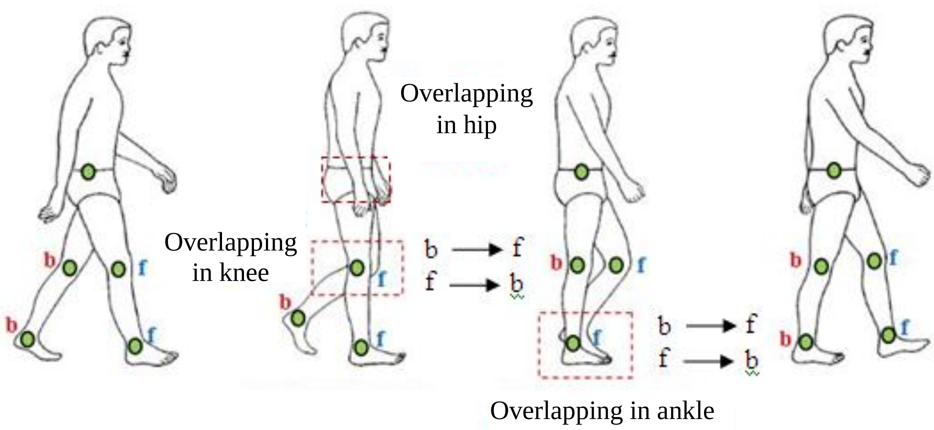


Figure 6. Overlapping condition

In the case of occlusion of markers, which may happen to the markers on the knee and ankle, a procedure to overcome the problem is proposed. A marker tracking program that has been developed in FMAE-ITB [18]-[19] is able to find the correct marker position after the overlapping occurs and changes the marker data arrangement. Figure 6 shows these overlapping conditions in a certain area of interest. For overlapping in the hip, the missing marker positions are approximated by interpolation as illustrated in Figure 7. The number of missing markers could be predicted from the number of blank frame in the area of interest. After that, the displacement (increment) of missing marker was calculated by dividing the gap with the number of missing marker, i.e. the number of blank frame, (m) plus 1. By this, all missing markers are equally spaced. After the displacements are known, the location of missing markers could be calculated.

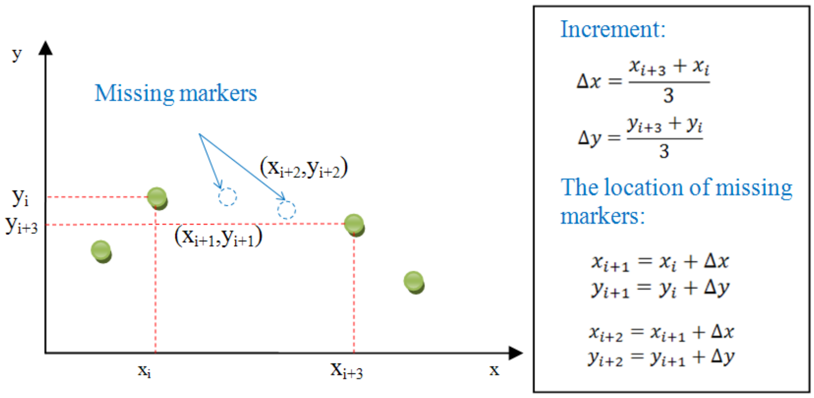
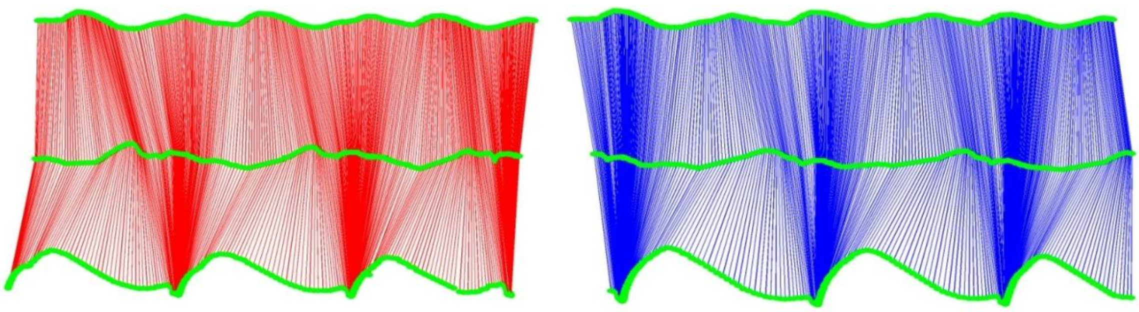


Figure 7. Interpolation to predict the missing marker location

In the final process, after marker detection and tracking procedure has been completed, by using calibration data, the marker's coordinates in image plane is transformed into the real world coordinate. Figure 8 shows representative frames with marker tracking result for hip, knee and ankle of left and right legs. Finally, using this data, several gait parameters, such as joint angle, step length and gait velocity could be calculated.



(a) (b)

Figure 8. Stick diagram animation (a) left leg markers (b) right leg markers

The Second Stage of Development (2D Motion Capture System)

The second system developed for gait analysis at FMAE-ITB is a further development of the first one to include foot data, which is very important so the system could provide more gait parameters, i.e. ankle angle, position of the centre of pressure and ground reaction force distribution. As shown in Figure 9, in the second system, the optical motion capture system consists of two cameras to record both left and right legs motions at the same time. This was done to avoid the overlapping of foot markers. A filter made of 20% window tint film was attached to the lens so the experiment could be conducted in a normal natural light environment. For this system, in addition to the five markers, previously located at hip both knees and both ankles, more markers were attached to heel and metatarsal joint [21], as shown in Figure 9.

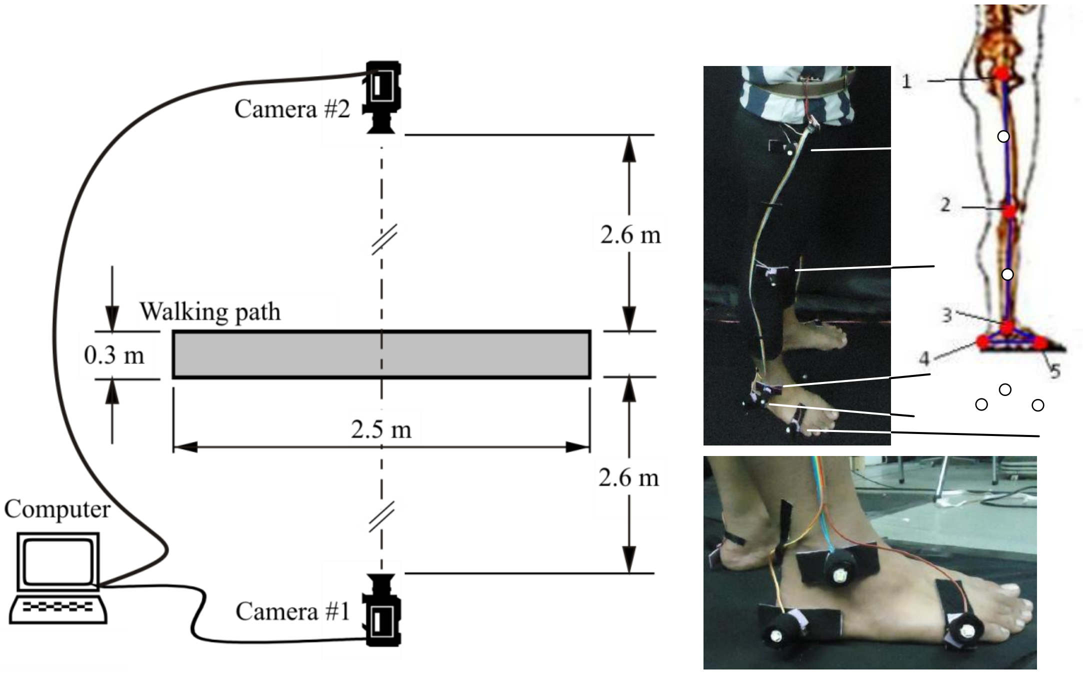


Figure 9. Description of the second 2D gait analysis system and marker positions

The DLT calibration process and image processing technique developed previously was then used to determine the coordinate of the markers. At first, when using a home video camera, the synchronization of the image frames obtained from both cameras was conducted by using light from a flash before the experiment started, to produce instantaneous light that could be captured by all cameras to mark the first frame. At the later stage of development, using 90 fps cameras connected to an image acquisition card installed in the PC, the synchronization of the cameras could be directly set from the computer.

Figure 10 depicts representative frames with marker tracking result for hip, knee, ankle, heel and metatarsal of left and right legs.

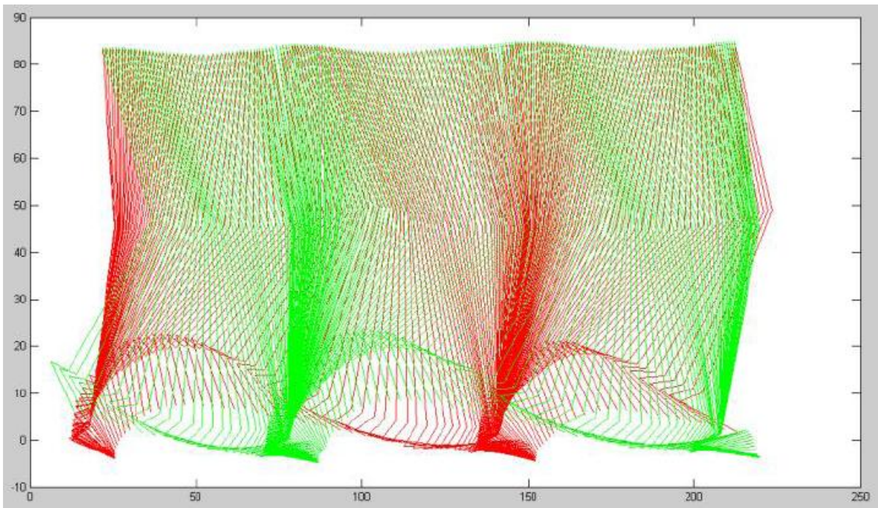


Figure 10. Stick diagram animation for both legs in the second development

The Third Stage of Development (3D Motion Capture System)

The experimental setup for the third stage of development [23] is shown in Figure 11. The length of walking path was designed to accommodate two steps. Two 25 fps home video recorders were positioned orthogonally, i.e. Camera #1 and #2, were used to acquire markers motions in sagittal and frontal planes, respectively. Each camera is connected to the computer using a firewire cable. For synchronization, in this experiment a flash was also used to mark the first frame. The markers used for motion tracking are LED that has spherical tip. Prior to recordings, a calibration process was conducted to obtain the unknown parameters of Direct Linear Transformation (DLT) using a known real world coordinate of eight markers as shown in Figure 12. For 3D gait analysis, seven markers are attached on seven positions of subject's leg, i.e. pelvis, hip, mid-thigh, knee, tibia, malleolus, and lateral metatarsal as could be seen in Figure 13.

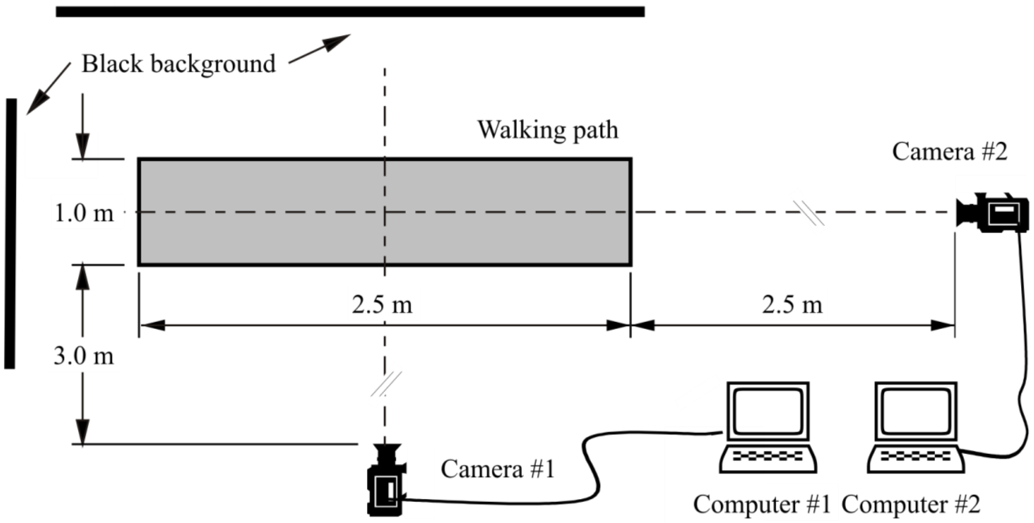


Figure 11. Description of the third development for the 3D gait analysis system

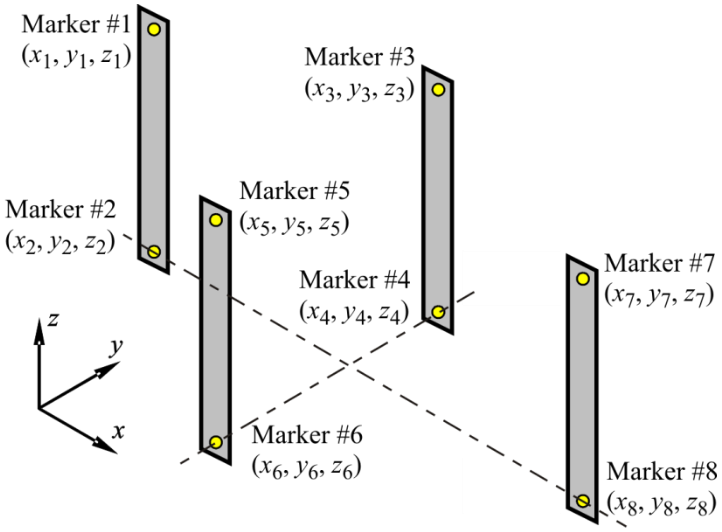


Figure 12. DLT markers for 3D calibration process

As in the previous development, recorded data obtained from experiment are then processed. Based on the frame showing the flash light, the frames of the two cameras were then synchronized. Using calibration images, the unknown DLT parameters were calculated. Marker detection and tracking process was conducted using the same technique developed in the first stage development. In this case there is no overlapping condition in video recorded by camera #2. However, it occurred in video recorded by camera #1, when the right hand prevented the observation of markers attached on pelvis or hip. Finally, as shown in Figure 14, marker tracking result could be displayed in both sagittal and frontal planes.

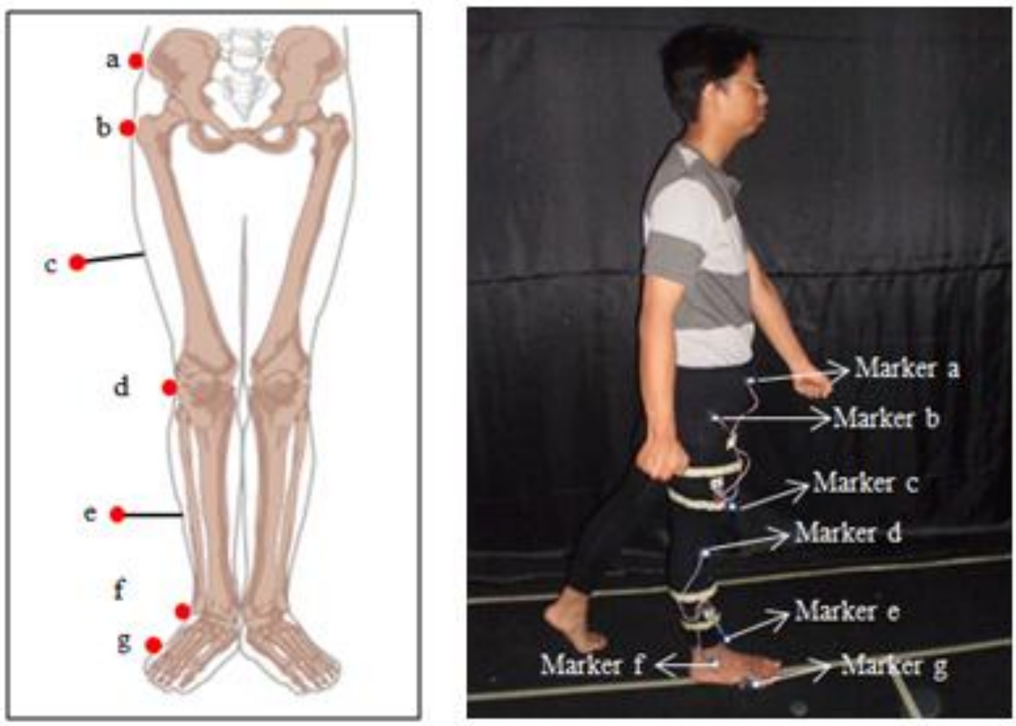


Figure 13. Position of the markers

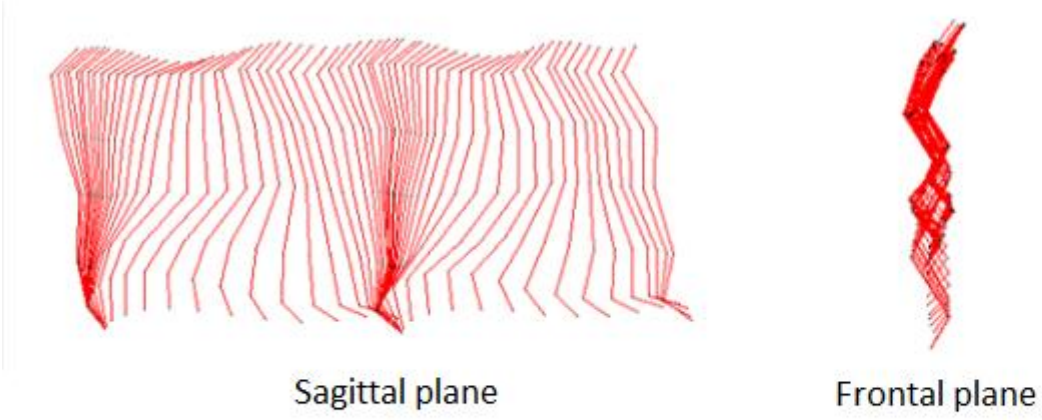


Figure 14. Stick diagram animation in sagittal and frontal planes

The development described in this section shows that the position of markers as a function of time could be obtained using a simple video camera and image processing system. The output is then used to obtain spatio-temporal gait parameters and for kinematic and kinetic analyses which will be discussed in the next section.

Kinematic and Kinetic Analysis

The Development of 2D Dynamic Analysis (Five and Seven Linkages)

In the development of 2D dynamic analysis, a multibody system of human body is modeled as linkages. At first it was modeled as five body segments [20], i.e. two segments of each lower limb and one segment representing the upper body part (including head, arms and trunk), and later it was expanded to become seven body segments [22], by adding foot segments, to provide ankle angle, position of the centre of pressure and ground reaction force distribution. Each segment is connected by joint as shown in Figure 15. The motion is assumed to be in the sagittal plane only. With this model, the mathematical formulation for dynamics analysis could be constructed. Using the experimental marker position and other variables such as segments lengths, body height and weight, kinematics and dynamics parameters of human gait were then calculated.

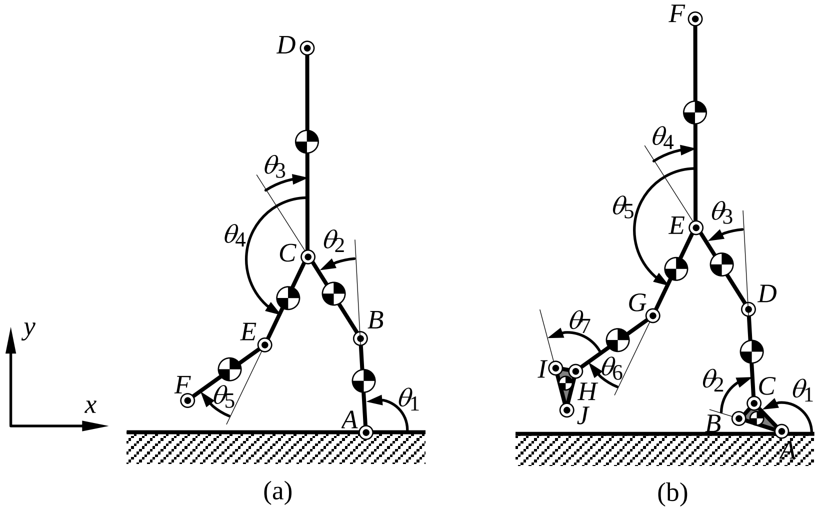


Figure 15. Human body model (a) five linkages (b) seven linkages

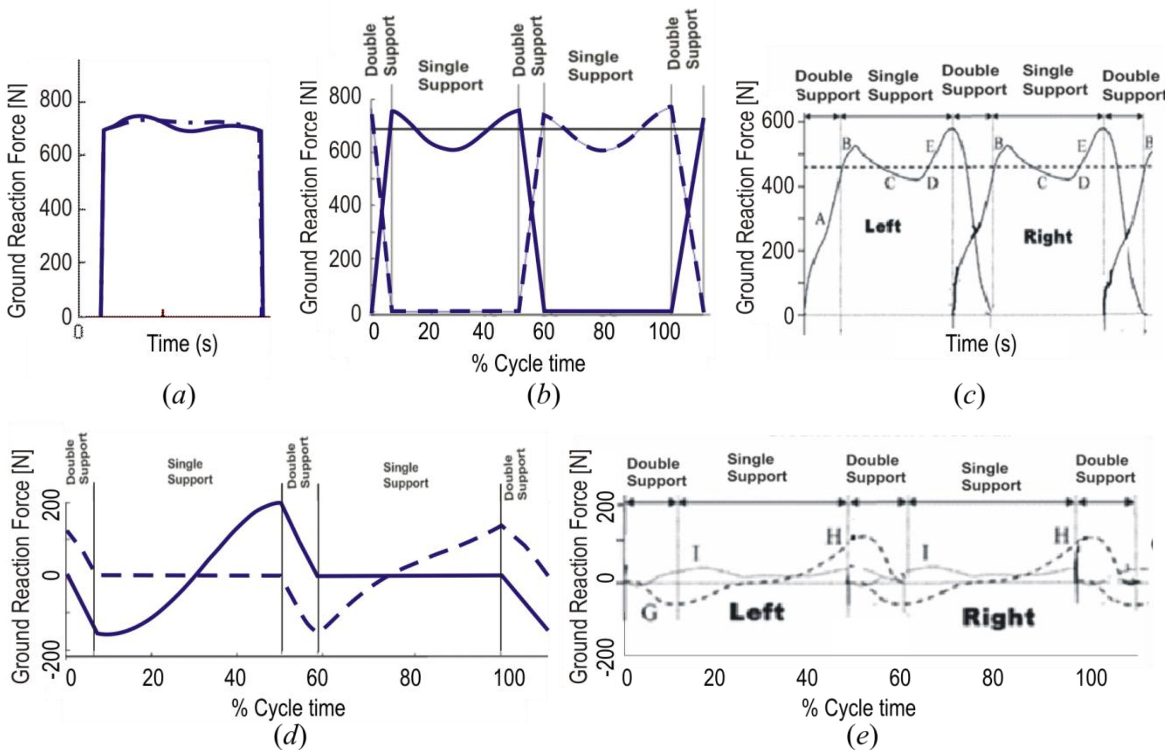


Figure 16. Ground reaction force in *y*-direction (a) five linkages (b) seven linkages (c) Hamill, 2009 [31] and in *x*-direction (d) seven linkages (e) Hamill, 2009 [31]

Figures 16-19 show several foot forces and moments calculated using these models. It may be seen that the results from the five linkages could provide initial understanding about gait parameter. The seven linkages model has been able to improve the results and yields a more accurate quantitative representation of forces and moment during human walking. Moreover, while the five linkage model has been able to provide a ground reaction force in y – direction, the seven linkages model provides a better result of ground reaction forces both in x – and y – directions.

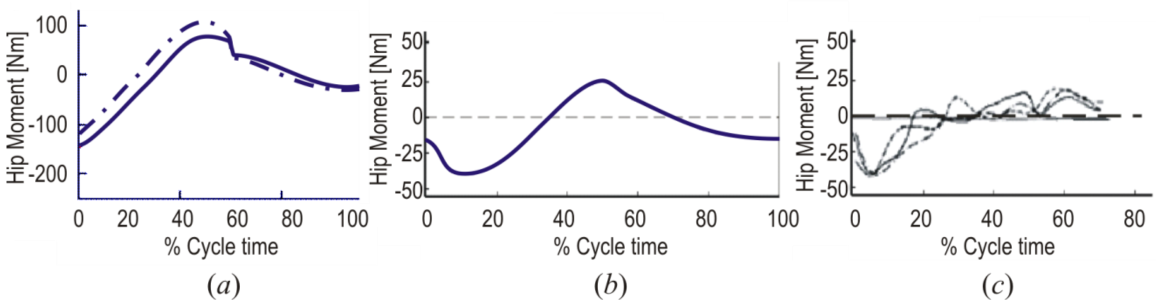


Figure 17. Hip moment (a) five linkages (b) seven linkages (c) Winter, 2009 [3]

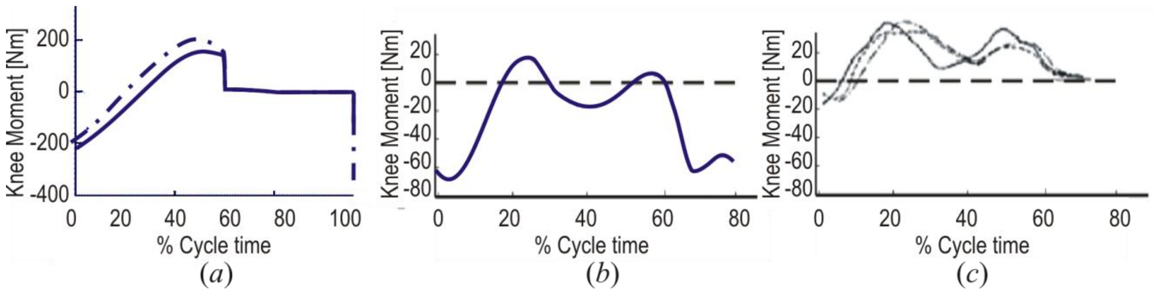


Figure 18. Knee moment (a) five linkages (b) seven linkages (c) Winter, 2009 [3]

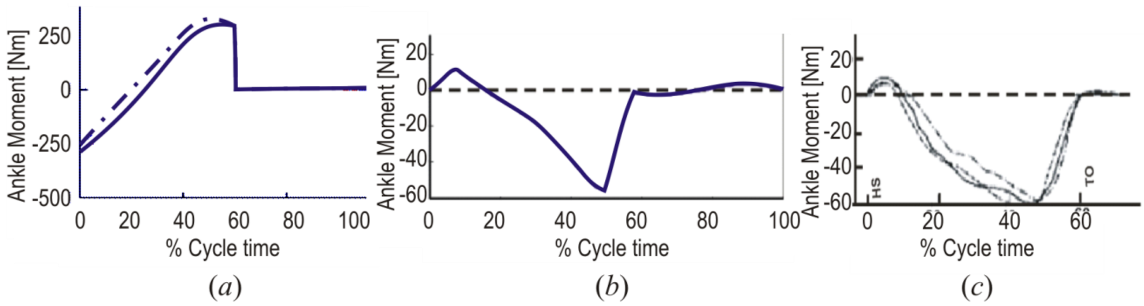


Figure 19. Ankle moment (a) five linkages (b) seven linkages (c) Winter, 2009 [3]

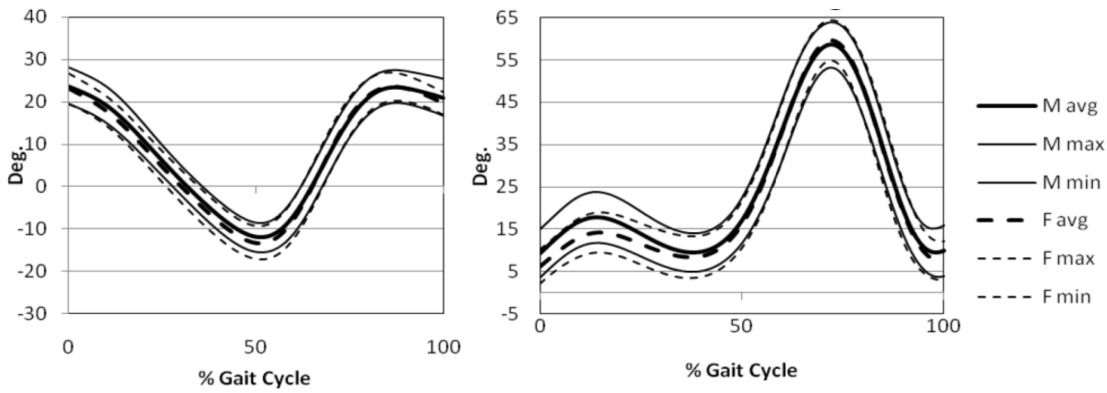


Figure 20. Hip angle (left) and knee angle (right) obtained using five linkages model

Figure 20 – 21 show joint angle obtained using five linkages and seven linkages model. It may be seen, both models are capable to capture the angle during gait cycle in relatively good accuracy. In the seven linkages model, not only hip and knee angle that could be obtained, but also ankle angle.

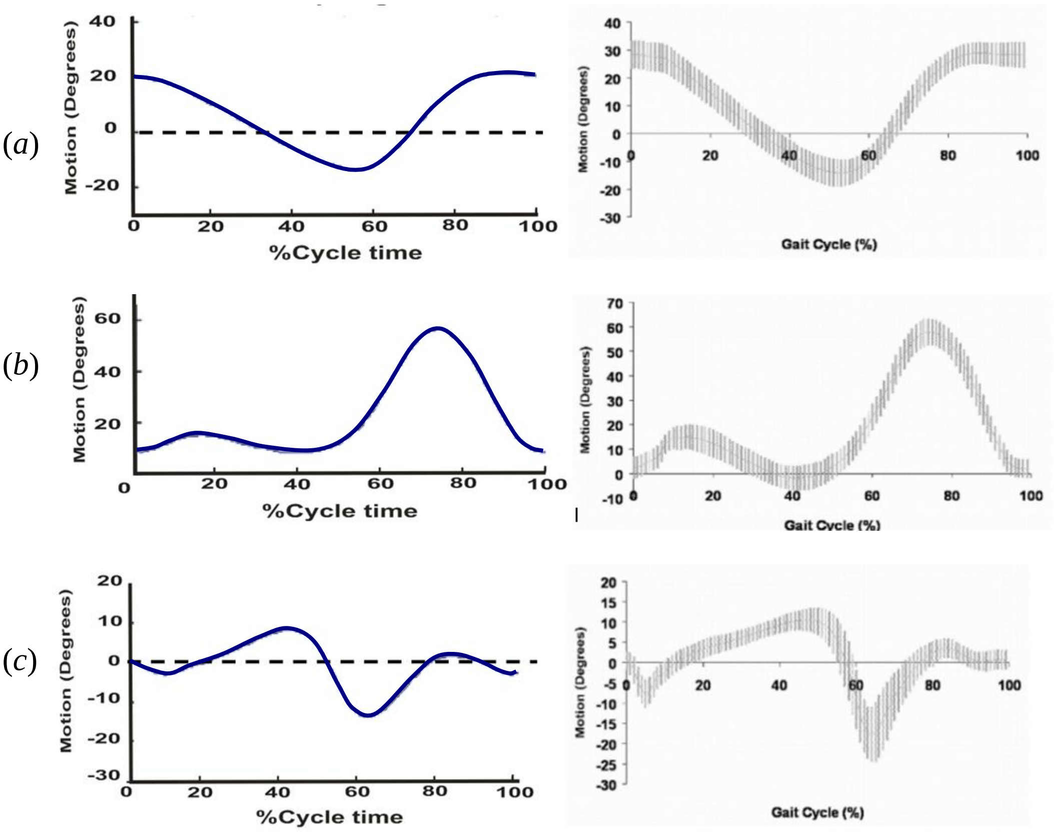


Figure 21. Hip angle (a), knee angle (b), and ankle angle (c) obtained using seven linkages model (left), compared to Rose and Gamble, 2006 [32] (right)

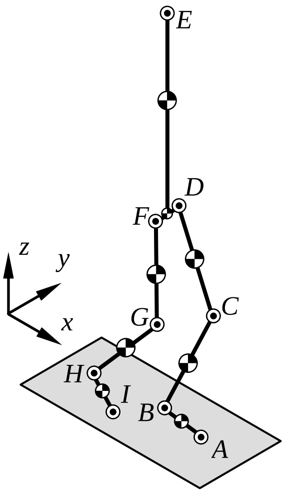


Figure 22. A 3D human body eight linkages model

The Third Stage of Development (3D Motion Capture System)

In the third stage of development, the human body was modeled as 3D linkages using eight segments as shown in Figure 22. This model was an improvement of a model introduced by Vaughan, Davis and O'Connor [33], where the human body was modelled as seven linkages, in which the pelvis and HAT (Head Arm Trunk) represented as one segment. In the present model, pelvis and HAT is divided into two segments, i.e. right foot, right calf, right thigh, pelvis, HAT, left thigh, left calf, and left foot.

The angular kinematics results of 3D models are presented in Figure 23. Here, the joint angles from three planes could be obtained, yielding more information for better understanding of the human walking.

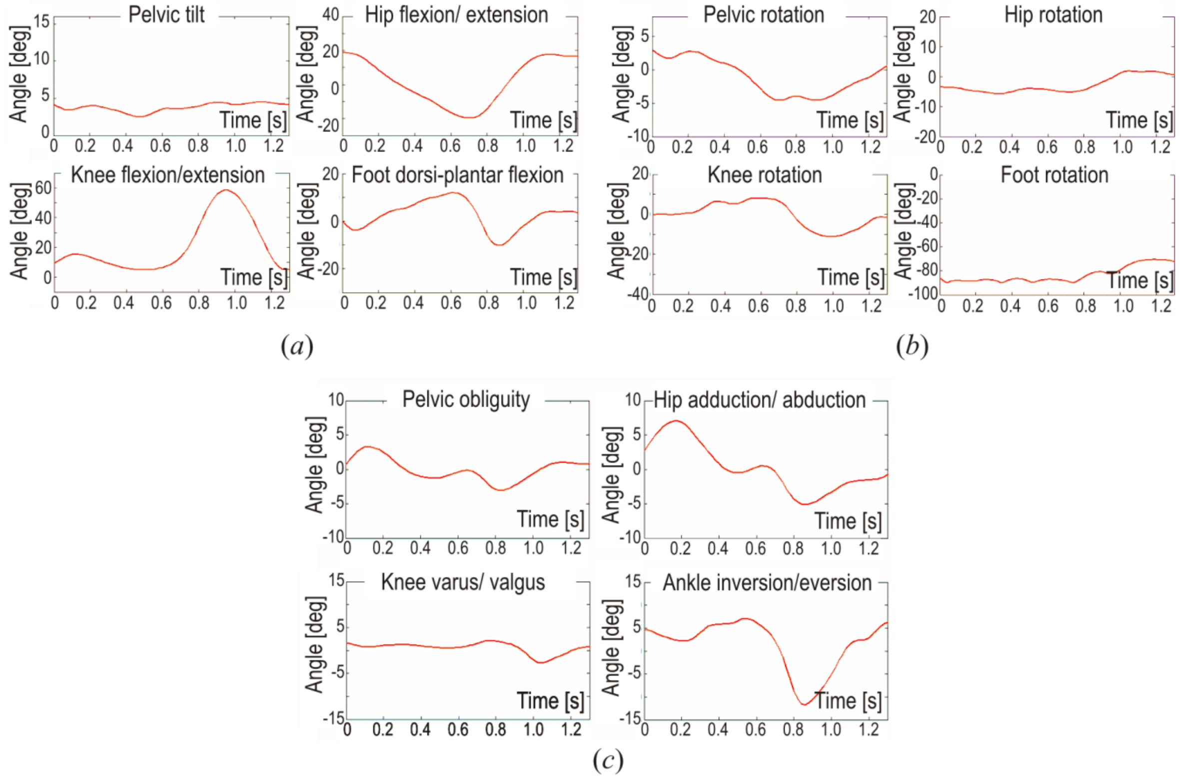


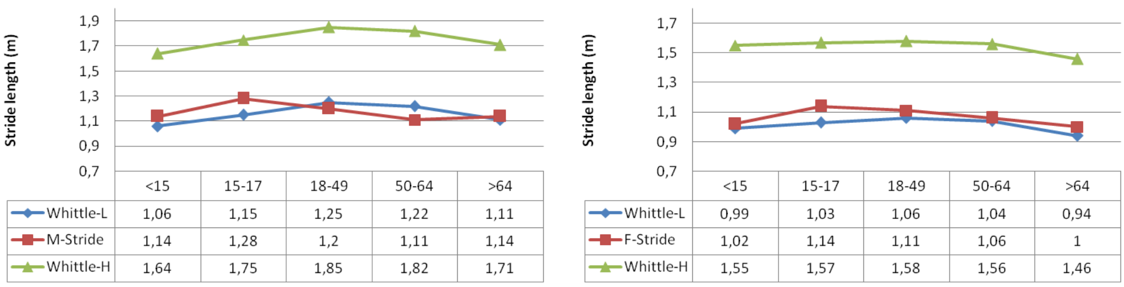
Figure 23. Joint angles (a) sagittal plane (b) transverse plane (c) frontal plane, obtained from the 3D human body eight linkages model

Indonesian Initial Gait Database

The 2D Optical Motion Analyzer developed in FMAE-ITB has been employed to collect normal gait data of 102 male and 110 female subjects from various age-groups and sexes and has been reported in [25][26]. Before the measurements, the body posture and body mass index (BMI) of each subject is evaluated to ensure normalcy. Only a subject with a normal posture and BMI will be included in the normal gait measurement. Table 1 and Figure 24 – 27 present several results obtained from the measurements of the subjects. It may be seen that, the Indonesian subjects have shorter stride length and slower cadence compared to the range given in Whittle [1]. While the shorter stride length may be attributed to the relatively smaller stature of the Indonesian subjects, the slower pace may be an indication of gait characteristics particular to Indonesian.

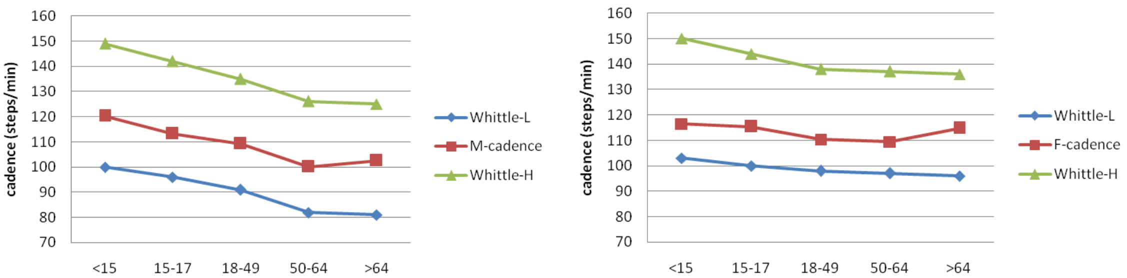
Table 1. Spatio-Temporal Gait Parameters of Subjects in 18 – 49 Age-Group

Variables	Male		Female		Whittle, 2007 (range); 18 - 49	
	Mean	SD	Mean	SD	Male	Female
Walking speed	1.09	0.11	1.02	0.12	1.10-1.82	0.94-1.66
Stride length (m)	1.20	0.08	1.11	0.10	1.25-1.85	1.06-1.58
Cadence	109.29	7.84	110.36	9.78	91-135	98-138
Cycle time (s)	1.10	0.13	1.10	0.14	0.89-1.32	0.87-1.22



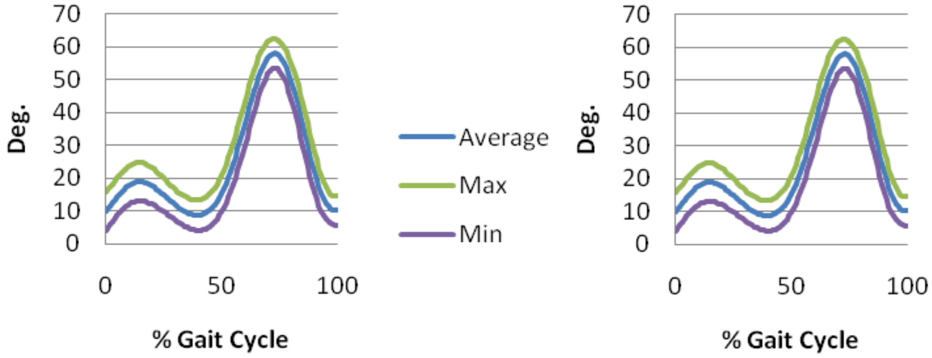
(a) (b)

Figure 24. Stride length vs Whittle [1] (a) male subjects (b) female subjects



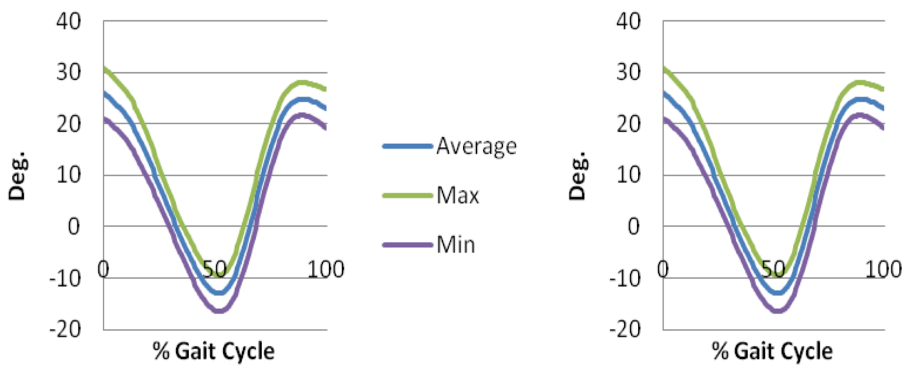
(a) (b)

Figure 25. Cadence vs Whittle [1] (a) male subjects (b) female subjects



(a) (b)

Figure 26. (a) knee angles of male 18-49 (b) knee angles of female 18-49



(a) (b)

Figure 27. (a) hip angles of male 18-49 (b) hip angles of female 18-49

The kinematic parameters in the form of maximum, average and minimum of knee-angles and the hip-angles for male and female subjects in the 18 – 49 age-group are presented in Figure 26 – 27, respectively. Similar motion patterns and excursions are observed for both male and female subjects. Comparison with available joint angular motion data in literature [1][4][29] as well as those presented in [25], show the results are in agreement. Thus, the data may serve as the initial basis for the establishment of normal Indonesian gait.

Conclusions

In this paper, the development of affordable, yet reliable systems for 2D and 3D gait analysis at FMAE – ITB has been presented. The system could successfully track the marker's movement during walking including at the time of occlusion. From the markers position data, several important gait parameters such as joint angle, step length and gait velocity, could be calculated. The developed programs could also perform kinetic analysis of human movement, where working forces and moments at joints can be calculated.

The main advantage of the present system is that it is relatively simple and cheap, costing little more than a home video camera, PC, and some dedicated software. Despite of that the system is quite reliable.

The developed system has been implemented for establishing database of normal Indonesian gait, which provides valuable quantitative information on Indonesian gait characteristics.

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