COMPARISON OF KINEMATIC RESULTS BETWEEN METU-KISS & ANKARA UNIVERSITY-VICON GAIT ANALYSIS SYSTEMS

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ABSTRACT

COMPARISON OF KINEMATIC RESULTS BETWEEN METU-KISS & ANKARA UNIVERSITY-VICON GAIT ANALYSIS SYSTEMS

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KISS (**Ki**nematic **S**upport **S**ystem) is a locally developed gait analysis system at Middle East Technical University (METU), and the performance of the system was evaluated before as a whole. However, such evaluations do not differentiate between the efficacy of the data acquisition system and the model-based gait analysis methodology. In this thesis, kinematic results of the KISS system will be compared with those of the Ankara University based commercial VICON (Oxford Metrics Ltd., Oxford, UK) system, in view of evaluating the performance of data acquisition system and the gait analysis methodology separately. This study is expected to provide guidelines for future developments on the KISS system.

Keywords: Gait analysis systems, comparison, data acquisition performance, model-based gait analysis methodology, identical motion data, joint kinematics.

ÖZ

ODTÜ-KISS VE ANKARA ÜNİVERSİTESİ-VICON YÜRÜYÜŞ ANALİZİ SİSTEMLERİNİN KİNEMATİK SONUÇLARININ KARŞILAŞTIRILMASI

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KİSS (**K**as **İs**kelet **S**istemi) Orta Doğu Teknik Üniversitesi'nde geliştirilmiş bir yürüyüş analizi sistemi olup, sistemin performansı daha önce bir bütün olarak değerlendirilmiştir. Ancak, bu tür değerlendirmeler veri toplama sistemi ile modele dayalı yürüyüş analizi metodolojisinin performanslarını ayırt etmeye olanak vermemektedir. Bu tezde KISS ve Ankara Üniversitesi'nde kurulu ticari VICON (Oxford Metrics Ltd., Oxford, İngiltere) sisteminin kinematik sonuçları karşılaştırılarak yukarıda anılan ayırımın yapılabilmesi amaçlanmıştır. Bu çalışmanın sonuçlarının ileride KISS sistemi üzerindeki geliştirmeleri yönlendirmesi beklenmektedir.

Anahtar Kelimeler: Yürüyüş analizi sistemleri, karşılaştırma, veri toplama performansı, modele dayalı yürüyüş analizi metodolojisi, özdeş hareket verisi, eklem kinematiği.

"Living beings have frequently been ... compared to machines, but it is only in the present day that the ... justice of this comparison [is] fully comprehensible."

Etienne Jules Marey (1830-1904)

"Mathematics is so different when applied to people. One plus one can add up to so many different things."

Werner Heisenberg (1901-1976)

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Ankara, 8 December 2006

Ezgi Civek

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LIST OF SYMBOLS

$\hat{C}^{(k,v)}$	Transformation matrix from F_v to F_k
F_v	Global coordinate frame used in VICON 370
F_k	Global coordinate frame used Kiss-DAQ
g	Gravitational acceleration
l	Length of pendulum
m	Mass of pendulum
n	Sample size
$\bar{r}^{(k)}$	Column matrix representation of vector $\vec{r}$ in F_k
$\bar{r}^{(v)}$	Column matrix representation of vector $\vec{r}$ in F_v
T	Period of pendulum

LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
Abd/Add	Abduction/Adduction
ACD	Ankle Centering Device
AJC	Ankle Joint Center
AL	Anatomical Landmark
Ant/Post	Anterior/Posterior
ASIS	Anterior Superior Iliac Spine
CCD	Charge Coupled Device
Dor/Pla	Dorsiflexion/Plantar flexion
EMG	Electromyography
Flx/Ext	Flexion/Extension
FPS	Frame Per Second
HJC	Hip Joint Center
Int/Ext	Internal/External
IR	Infrared
JCS	Joint Coordinate System

KCD	Knee Centering Device
KJC	Knee Joint Center
LED	Light Emitting Diode
SCS	Segment Coordinate System
Val/Var	Valgus/Varus
VCR	Video Cassette Recorder

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Classical or Newtonian mechanics is a branch of physical science that concerns with the behavior of bodies under the action of forces. Biomechanics is the application of Newtonian mechanics to living organisms, especially to human body.

Biomechanics is a broad field with diverse applications. Human motion is one of the popular subjects in this field, and has a long history. The comprehensive study of human motion dates back to 1800s. Weber Brothers (*Mechanik der menschlichen Gehwerkzeuge*, 1836) reported the first quantitative studies of human locomotion, and later on Marey (*Animal mechanism: A treatise on terrestrial and aerial Locomotion*, 1873) and Muybridge (*Animal locomotion*, 1887) recorded human movement using photographic techniques (Figure 1.1) (as cited in Andriacchi and Alexander, 2000).

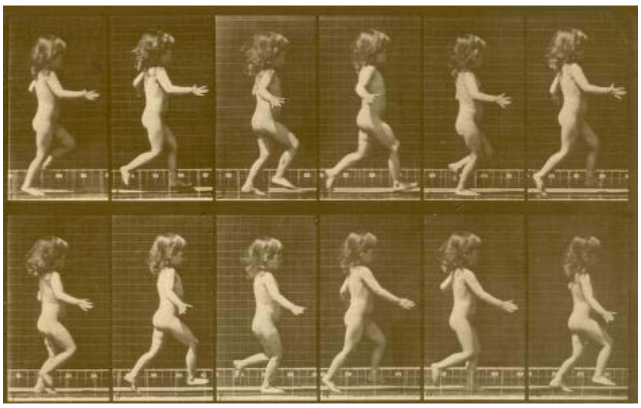


Figure 1.1 Muybridge Animal Locomotion, Plate 469: Movements, Female, Child, running (Adapted from http://www.archives.upenn.edu/primdocs/upt/upt50/upt50m993.html)

Early motion analyses based on film photography was generally limited to one plane, and those imaging systems lacked the capability of automated data reduction. Therefore, frame by frame manual digitization procedure, which is really laborious and time consuming, was required in order to obtain motion data. In the late 20^{th} century, with the rapid advances in specialized measurement equipment and techniques and with the development of powerful computer systems, it became possible to perceive and process the information regarding the three-dimensional motion faster.

1.1.1 Gait Analysis

Gait analysis can be described as a subfield of biomechanics dealing with the subject of fundamental human motion, i.e. gait. According to the definition given by Davis, Õunpuu, Tyburski and Gage (1991), gait analysis is the systematic measurement, description, and assessment of those quantities thought to characterize human locomotion.

Modern gait analysis started with the work of Eberhardt and Inman in 1950s. Further important contributions to the field were made by Bresler and Frankel (1950), Saunders et al. (1953), Cavagna and Margaria (1966) (as cited in Whittle, 2002). Then, gait analysis became a useful clinical tool through the pioneering efforts of Sutherland (1964) and Perry (1992).

Quantitative gait analysis focuses on kinematics, which is the branch of mechanics dealing with the motions of bodies without being concerned with the forces that cause the motion or are due to the motion. Kinematics describes the spatial and temporal aspects of motion such as positions, angles, linear and angular velocities and accelerations of body segments and joints during motion. Quantitative gait analysis also permits the calculation of kinetics, which is the study of forces and moments acting on a body.

Through gait analysis, human gait data are captured by means of different measuring techniques, and then further analysis and calculations are done in order to obtain all the information required for the assessment of subject’s gait, including basic gait parameters, variations in joint angles, resultant forces and moments occurring in the joints and the muscle activity during each gait cycle.

Gait cycle is the single sequence of events between two successive occurrences of one of the repetitive incidents of walking as Whittle (2002) defined. It is frequently more convenient to use the instant of initial contact of one foot to the ground as the starting point of the gait cycle, and the cycle terminates when the same foot makes contact with the ground again. Figure 1.2 illustrates a single gait cycle from right heel contact to right heel contact.

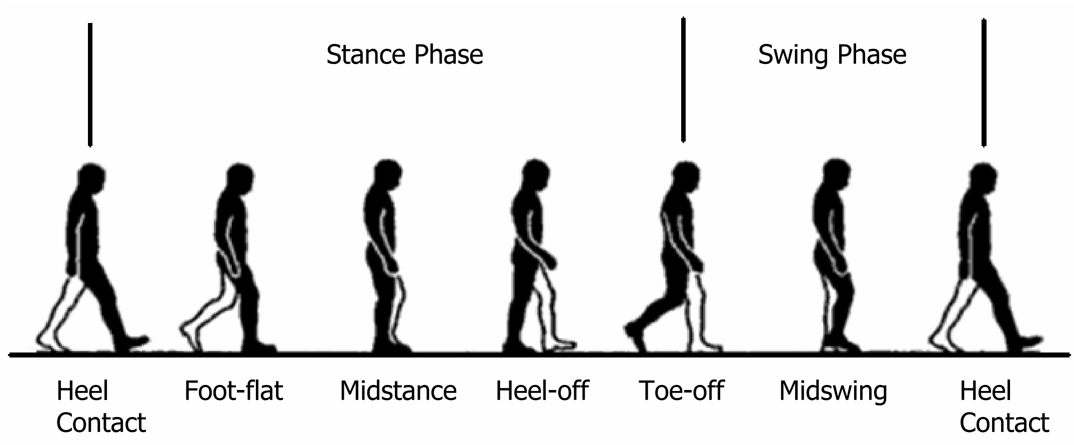


Figure 1.2 Positions of the legs during a single gait cycle
(Adapted from *Three-Dimensional Analysis of Human Movement*, by P. Allard, I. A. F. Stokes, & J. P. Blanchi, 1995, USA: Human Kinetics)

Gait cycle is divided into two phases. In normal walking, each leg goes through a period when it is in contact with the ground, which is called stance phase, and a period where it is not in contact with the ground, called swing phase. For natural walking, stance phase usually lasts about 60 percent of the cycle, and the swing phase is about 40 percent of the cycle.

Within each phase, there are certain time instants which are of great importance for the analysis of gait. The names of these events are self-descriptive and are based on the movement of the foot, as seen in Figure 1.2. "Heel strike" or also called "heel contact" initiates the gait cycle. "Foot-flat" is the time when the plantar surface of the foot touches the ground. "Midstance" occurs when the swinging foot passes the stance foot. "Heel-off" occurs as the heel loses contact with the ground.

“Toe-off” terminates the stance phase as the foot leaves the ground. “Midswing” occurs when the foot passes directly beneath the body.

The gait cycle is also identified by the term stride, which is the interval between two sequential initial contacts of the same foot. Step, which is occasionally confused with the word stride, is the interval between initial contacts with one foot and then the other foot, consequently step length for a healthy individual is the half of the stride length. Figure 1.3 illustrates the terms used to describe the distance parameters characterized by the foot placement on the ground.

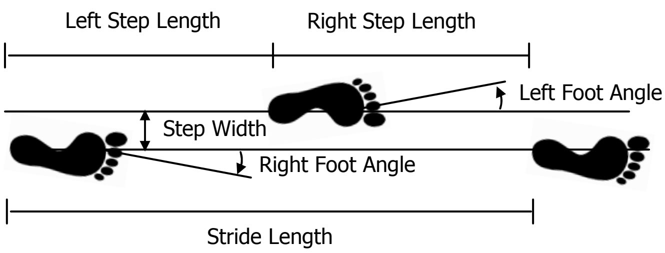


Figure 1.3 A person’s footprints that characterize useful distance parameters

Cadence is the number of steps taken in a given time. Basic gait parameters such as stride length, step length, cadence, (average) speed of walking, etc. are the spatio-temporal quantities calculated from geometric and temporal data.

Gait analysis has a widespread use today in a variety of applications in almost all considerable fields of human movement, for both clinical and research purposes. Gait analysis plays a key role in the clinical decision making processes such as diagnoses of disorders, as well as future treatment plans in physical medicine and rehabilitation. Gait analysis also allows the quantification of the effects of rehabilitation and orthopaedic surgery. Aside from clinical applications, gait analysis is widely used in professional sports training to optimize and improve athletic performance, and also in entertainment industry like movies, video games and virtual reality applications.

1.1.2 Gait Analysis Systems

Since gait analysis has a wide area of application involving both clinical and research purposes, there are various methods that may be used to perform gait analysis.

The simplest way of evaluating the human walking is the visual gait analysis, which is an essential skill for a clinician, and requires no equipment. Such qualitative methods are lack of repeatability, consistency, accuracy and precision compared to quantitative methods.

With the advances in instrumentation technology, quantitative methods are improved, and several types of equipment have been developed for recording the motion of joints and segments of the body. These include electrogoniometers, accelerometers, electromagnetic systems and imaging systems.

Imaging systems for motion analysis can be further divided into two main subgroups: film photography and automated motion capture systems. Film photography requires manual digitization, whereas automated motion capture systems automatically produce digital data of the recording.

Optical motion capture systems enable the recording of only the motion of markers placed upon specific anatomical bony landmarks of the subject, rather than the whole body motion. These systems consist of either passive or active markers. Passive markers, also called as reflective markers, are solid shapes covered with retroreflective tape, and so they reflect a signal. Active markers, also called as emissive markers, are generally infrared light emitting diodes (LEDs), which emit a signal. Motion capture systems that utilize active markers are named as optoelectronic systems.

Motion capture systems enhanced with passive markers are the most frequently used type of motion analysis. In this work, two different motion capture systems using passive markers were compared. Therefore, passive marker systems will henceforth be described in details, and referred to as gait analysis system.

A gait analysis system requires one or more cameras to track passive markers. In order to determine the three dimensional coordinates of the markers, at least two cameras with non-parallel image planes are required.

Passive markers attached to the anatomical landmarks reflect either external ambient light or camera projected light, generally infrared. The light reflected by the markers comes back into the camera lens, and the digital image signal produced on camera plane is fed into the computer.

In three-dimensional systems, computer software computes the 3D trajectories of each marker relative to a laboratory-fixed coordinate system by 3D reconstruction using stereo (two) image sequences. These two images can be acquired by either two cameras at the same time or by one camera at a different time instant. Therefore, two types of matching are essential to acquire the path followed by the markers during subject's motion, temporal and spatial matching. Temporal matching is the matching of one marker's image in successive frames (in time), whereas spatial matching associate marker's coordinates among the corresponding images in different cameras. In order to determine all parameters for reconstruction procedures, camera calibration and lens distortion parameters are also required to be known.

Figure 1.4 illustrates the schematic diagram of a gait analysis system. Force plates, electromyography (EMG) and pedobarograph are employed in gait analysis laboratories in order to obtain data related to kinetics of motion.

Force plates are transducers to measure the ground reaction force resultants as forces along three orthogonal axes and moments around these axes when a subject walks across it. EMG measures electrical activity of contracting muscles and pedobarograph is for the measurement of pressure distribution on the bottom of the foot through gait cycle.

A typical gait analysis consists of three parts:

- Data Acquisition
- Data Processing
- Data Analysis

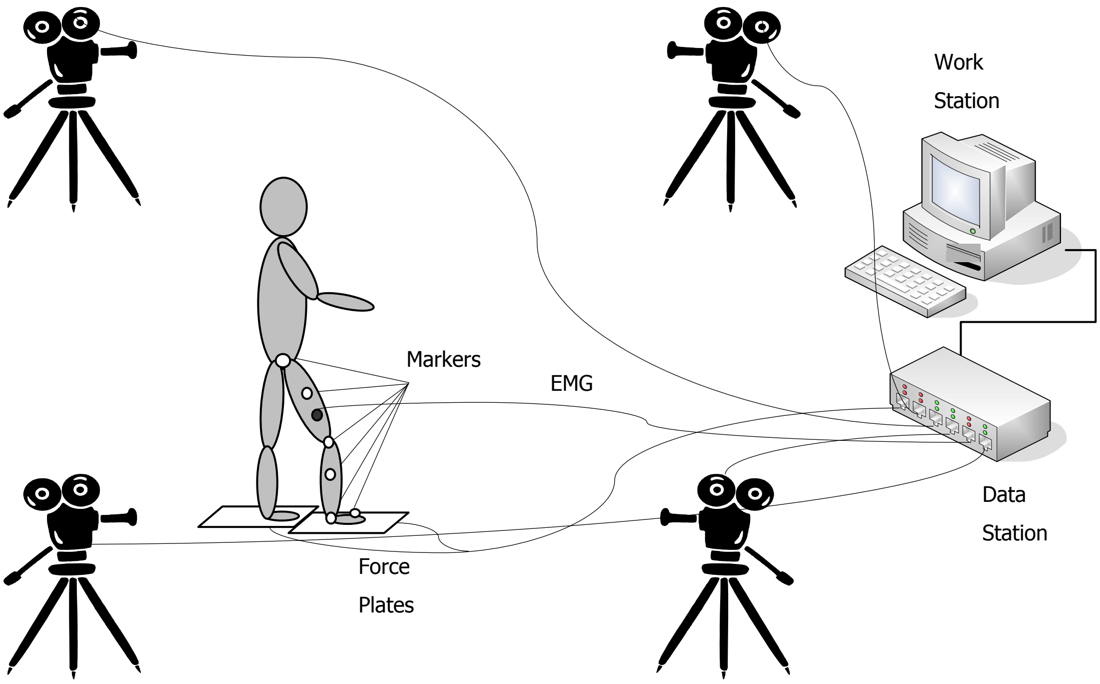


Figure 1.4 Schematic Diagram of a Gait Analysis System

1.1.2.1 Data Acquisition

Any gait analysis laboratory has data collection units in order to obtain the required data for calculation of joint kinematics and kinetics. The reliability and the accuracy of the data are extremely important features in data collection. There are quite many factors that affect the data accuracy.

Camera configuration is one of them. Both the number of the cameras and the placement of those in the laboratory space are important. In practice, more than two cameras are necessary; especially five or six cameras are preferred to achieve reasonable accuracy in 3D kinematic measurement, since markers can be obscured from camera view because of arm swings, laboratory configuration, etc. On the other hand, optimum settings should be found because as Shafiq (1998) asserted that multiple cameras increase the overlap while reducing marker drop out. Furthermore, Bontrager (1998) advised several principles in order to maximize data collection accuracy by minimizing potential sources of error due to the laboratory configuration.

Ambient noise is another source of error in data acquisition. Laboratory environment should be selected that minimizes noise, and appropriate filtering techniques can be applied.

The location of the markers with respect to anatomical landmarks is critical to the overall accuracy of the system. The configuration of specific locations of markers is named as marker set. Harris and Wertsch (1994) indicated that marker sets are designed considering the fact that a plane for each body segment is defined by at least three markers, and aiming to maximize the distance between markers to prevent image overlap and sorting difficulties. Therefore, widely employed marker sets in gait analysis use 13 or 15 markers to define 7 body segments. In these marker sets, three markers are placed on each limb segment for carrying out a 3D analysis and joint markers are usually shared by adjacent segments.

In gait analysis, marker set is coupled to a biomechanical model. Several gait analysis models are available in the literature; gait models developed by Davis et al. (1991), Kadaba, Ramakrishnan, and Wootten (1990) and Vaughan, Davis, and O'Connor (1992) are the most widely employed ones. Most of kinematic models assume that the body is composed of rigid segments that are connected by ideal linkages as Andrews (1995) emphasized. Therefore, gait analysts must have excellent palpation skills for the marker placement in order to avoid misalignment of markers, and prevent skin movement artifacts.

Marker and model combination allows calculation of joint and segment kinematics, i.e. angular and linear positions, velocities and accelerations of body joints and segments with respect to either a fixed laboratory coordinate system or with respect to another body segment.

In any motion analysis system, an accurate method of system and camera calibration is needed in order to minimize sources of error. By taking the advantage of placing markers at known locations in the laboratory, calibration parameters to be used in 3D reconstruction from 2D camera data can be estimated. After the calibration parameters have been calculated and stored, it is crucial that camera positions remain unchanged throughout the data collection. A new calibration is required when the cameras have been moved either deliberately or accidentally. In a clinical laboratory, it is recommended that calibration be performed at frequent intervals, certainly at least once per day. Linearization is also required to be performed from time to time in order to correct the lens distortion errors in the cameras.

1.1.2.2 Data Processing

Data processing includes filtering and differentiation procedures that take place following the data acquisition. Prior to running the processing procedures, marker identification and 3D reconstruction of markers are performed.

The primary kinematic data provided by a gait analysis system is position. Numerical differentiation procedure is required in order to obtain velocity and acceleration from the position data. Thus, the accuracy of position data is an important issue. In order to maintain system accuracy, filtering (smoothing) must be applied to the sampled data contaminated with noise before differentiation, since differentiation magnifies high frequency noise. Random noise is usually characterized by high frequency content, whereas the movement signal is generally limited to a band of low frequencies. It is, therefore, customary to use a low-pass filter to remove the high frequency components and retain those of the low frequency, the movement signal.

1.1.2.3 Data Analysis

After data processing, data analysis procedure arises. At the end of the gait trial, it is required for a motion analyst to complete all the necessary analysis steps such as marker labeling and event detection (determination of the instants of heel strike and toe off).

Motion data is then processed using a gait model, and presented in report for review, interpretation and discussion. Gait model combines the movement, force plate and EMG data with patient specific anthropometric measurements, such as height, weight, leg lengths, and knee and ankle widths, to determine the joint center locations, segment orientations, mass center locations, mass moments of inertia, and three dimensional joint angles and moments.

1.2 Scope and Outline of the Thesis

1.2.1 Statement of Clinical Significance

Clinical decision making processes such as diagnoses, treatment planning and evaluation based on gait analysis results advanced in the last two decades, and applications of gait analysis have started being frequently used worldwide. Since then, many companies have developed software packages to analyze gait data captured with their hardware systems. There are now a wide variety of gait analysis systems available in the market, and some of them are VICON (Vicon Motion Systems Ltd., Oxford, UK), PEAK (Peak Performance Technologies, Inc., Englewood, CO, USA), QUALISYS (Qualisys Medical AB, Gothenburg, Sweden), ELITE (Bioengineering Technology and Systems, Milano, Italy), OPTOTRAK (Northern Digital, Inc., Waterloo, Ontario, Canada), APAS (Ariel Dynamics, Inc., Trabuco Canyon, CA, USA), CODA (Charnwood Dynamics Ltd., Leicestershire, UK), etc.

These systems differ from each other in both data acquisition system and model-based gait analysis methodology. Consequently, these software packages lead to different results. These results, however, may or may not be significantly (or clinically) different. Therefore, a comparison of results from different gait analysis systems is required in order to determine whether or not there were any significant differences between the calculated kinematics of different gait analysis programs, and to investigate how comparable these results are.

Currently, analysis results from different laboratories cannot be compared since it is not known whether the analysis methodologies in different systems are similar enough to yield comparable results. For this reason, gait analysis laboratories are required to develop their own databases in order to evaluate and interpret gait analysis results in a more efficient and reliable way.

The ability to gather large samples of data and to have an extended database characterizes the gait data of both able bodied and pathological subjects having specific attributes such as age, gender, height and weight is extremely important for clinical research. Building up such an extended database is difficult for a single gait laboratory. However, if different gait analysis systems are verified to give a high degree of similar results for the same motion data, then gait laboratories having different systems could collaborate with each other, and could enhance their database available.

1.2.2 Scope of the Thesis

One way to compare different gait analysis systems would be to study the same subject on each system. However, human gait by nature has variability even within individuals. Other possible error factors related to the subject, performer and the laboratory conditions could not be avoided in the experiments. On the other hand, even if all sources of variability are controlled, let the subject walk exactly the same manner in the experiments performed in each system, or let the experimenter place the markers exactly on the same locations, to capture and analyze gait trial of the same subject with two systems would enable just an evaluation of the system as a whole. Such a comparison methodology would not be possible to test the biomechanical model and algorithm used to calculate the joint angles. Hence, this approach would not be adequate to obtain a definitive comparison.

Another way would be to analyze the same motion data captured with one hardware on various systems, thus a direct comparison could be made between the software responsible for calculating joint kinematics.

The two gait analysis systems compared in this thesis are METU-KISS and Ankara University VICON gait analysis systems. KISS is a gait analysis system locally developed at Middle East Technical University, and VICON is a commercial motion capture system manufactured by Oxford Metrics Ltd., and has been in use since 1997 in Ankara University.

In the scope of this thesis, both of the two methodological approaches mentioned above were implemented. For the same subject, gait experiment was conducted in both KISS and VICON systems. Motion data regarding the subject's walking trial was captured and reconstructed by data acquisition software of the system on which experiment was conducted, and then 3D reconstructed data was given as an input into gait analysis software packages of both KISS and VICON separately, and the kinematic analyses were performed in both systems using the same kinematic data.

Since both KISS and VICON store data in different file formats, data cannot be interchanged freely. Therefore, the data of each system must be converted to be read by the other system's programs.

VICON uses a widely used common format for storage of motion data – so called "C3D file format" whose file specification is published, and freely accessible (c3dformat.pdf, 2006). File conversion procedures between KISS and VICON have been achieved by user-written programs and various C3D software applications available in the market that give the opportunities of viewing, editing and creating gait trial data.

Once the file conversion tools between KISS and VICON have been available, these gait analysis systems gained the ability to read and analyze each other's motion data. Thus, both laboratories could enhance their database without conducting experiments, i.e. by performing the analyses of the gait data recorded in the other laboratory's experiments. Moreover, METU-KISS gait analysis system has become compatible with a widely used common data file format, known as C3D, which was one of the leading objectives of this thesis.

If it is concluded that these two systems yield very similar outputs for the same set of data according to the outcomes of this study, then conversion may not be necessary. Gait analysis results obtained from both systems could then be legitimately combined and studied without regard to slight algorithm differences that may be present. Hence, METU and Ankara University gait analysis laboratories could construct their common database by establishing a close collaboration between each other.

1.2.3 Outline

This thesis is organized as follows:

Chapter 1 is the introduction to the thesis. It provides an overall view of the thesis and discusses the background including the gait analysis and the gait analysis systems, statement of clinical significance and briefly the scope of the thesis.

Chapter 2 gives the historical development of motion analysis techniques, and discusses currently available motion capture systems. The existing research concerned with the comparison studies of various motion capture systems in the literature are presented, in addition to introducing a common C3D file format widely used within the biomechanics community.

Chapter 3 compares the two motion analysis systems, namely KISS and VICON, in four main sections such as system descriptions, data collection protocol, data reduction protocol and file types.

Chapter 4 focuses on the instrumental error and compares the data acquisition performance of the two motion analysis systems KISS and VICON in terms of relative accuracy and precision.

Chapter 5 compares the kinematic results of the KISS system with those of the Ankara University based commercial VICON system, in view of evaluating the gait analysis methodology.

Chapter 6 represents the conclusion of the whole study. It also includes a brief summary of the contributions of this thesis and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 MOTION CAPTURE SYSTEMS

2.1.1 History and Development

Modern studies of human locomotion are based on the studies that can be traced back to the end of the 19th century. The works of two contemporaries Marey (1873) and Muybridge (1887) are the landmarks in the development of motion capture. The English photographer E. Muybridge used a series of cameras located along a racetrack to take multiple pictures in rapid succession to study horse locomotion. Muybridge then applied his technique to study human motion.

The French physiologist E. J. Marey also studied animal and human locomotion. Whereas Muybridge had used a number of cameras to study movement, Marey used only one, and the movements had been recorded on a rotating photographic plate. Ladin (1995) pointed out that, Marey improved the performance of his photographic equipment by introducing the first *passive markers*.

Marey's technique for capturing motion involved metal stripes or white lines attached between the main joints of the extremities and they reflected light onto a photographic plate as the subject passed in front of the black backdrops. The subject wore black suit to improve the contrast of the image (Figure 2.1 & Figure 2.2).

W. Braune and O. Fischer (*Der Gang des Menschen*, 1895) described an improved process for studying human motion. They attached long, thin light tubes to the body segments and used pulses of electric current to generate short bursts of light, synchronously photographed by four cameras. This approach represents the origin of the *active marker* systems used today in many biomechanics studies. Braune and Fischer were able to study both the spatial orientation and the time derivatives of the spatial coordinates of the segments of interests by reconstructing three-dimensional coordinates of the marker. The process of collecting data required about 12 hours per subject and then it took up to 3 months to analyze the data (as cited in Ladin, 1995). Since it was so time consuming, this technique could only be applied in gait research.

Figure 2.1
Marey's motion capture suit

Figure 2.2
Exposure showing model as well as suit markers

(Adapted from http://www.acmi.net.au/AIC/MAREY_BIO.html)

As being cited by Sutherland (2002), Eberhardt and Inman also included the use of interrupted light in the late 1940s. They photographed the subject walking while carrying small light bulbs located at the hip, knee, ankle and foot. A slotted disk was rotated in front of the camera, producing a series of white dots at equal time intervals. These dots then connected to provide joint angles. This was also a slow and labor intensive process.

Furthermore, Inman recorded the movement of the pins drilled into the pelvis, femur and tibia by a camera located above the subject in order to examine transverse plane rotations. This method was not suitable for clinical application, but there has been some recent use of pins inserted into bones in order to determine the difference between movement of markers affixed to the skin surface and those placed into the skeleton.

A major development came with the development of small computers. With the progression of video technology in the mid 1970s and the accompanying increase in the computer power, less labor intensive systems became available. E. H. Furnée (1989) began late 1960s to develop TV/motion analysis systems with automated recording of reflective marker positions. He is the originator of the PRIMAS system developed at Delft University of Technology. Besides Furnée et al. (1974), Jarrett, Andrew and Paul (1976) and Winter, Greenlaw and Hobson (1972) were the developers of the first video camera based systems (as cited in Pedotti and Ferrigno, 1995).

The systems developed in those years forms the basis of the currently available motion analysis systems. Gill et al. (1997) indicated that the huge strides in the motion capture technology had taken place around 1980 when the first commercial systems became available.

The latest generation systems using pattern recognition techniques for marker detection appeared in the late 1980s, that kind of threshold based systems and their application areas were covered in the review papers authored by Aggarwal and Cai (1999) and Moeslund and Granum (2001).

2.1.2 Motion Capture Technologies

Today, various motion capture systems are available in the market. There are two categories of optical motion capture systems commonly used to measure human motion; those are passive and active systems depending on the type of markers that each system utilizes.

Active marker systems usually employ LEDs which are triggered and pulsed sequentially by a computer, so marker tracking is not a problem. System automatically knows the identification of each marker. No marker merging occurs in these systems; hence the markers can be placed close together, permitting use of a larger number of markers. They offer the advantages of higher sampling rates and frequency coded data sorting. However, these systems require that power pack and the wire connection from LEDs to the datastation has to be delivered on the subject's body. This makes measurements cumbersome and limits them with the laboratory environment. Heat generated by the LEDs might be a problem for long duration experiments.

Passive marker systems have the advantage of using lightweight reflective markers without the need for cables and batteries on the user. But they require illumination source typically infrared (IR) usually mounted around each camera lens. IR light, sent out from the camera is reflected back into the lens by the markers. IR pass filters placed over the camera lenses and set threshold automatically discriminate the marker. Because all markers are visible at any given time, potential merging of markers places limitations how close together markers may be placed.

Each marker trajectory must be identified with a label and tracked throughout the test. For this purpose, these systems require the use of sophisticated algorithms to identify the center marker positions for accurate tracking. When markers are lost from view or their trajectories cross, they can lose their proper identification. If a marker is occluded, some systems supply the missing point by interpolation and user intervention post processing are sometimes required.

Most of these systems have CCD (charge coupled device) cameras that are directly connected to a computer. There are a few number of systems in the market that use a VCR (video cassette recorder) for recording the motion of markers. In these systems the whole image is recorded to videotape, and the marker coordinates later derived by processing the tape with a computer-controlled VCR. Recording the whole video image allows recording to take place almost anywhere with an ordinary camcorder. However, tape processing is time-consuming.

Systems operating with the electromagnetic principle are also available in the market. Electromagnetic systems are based on low frequency magnetic coils allowing 3D tracking by sensors placed on the segments. These tracking systems are fairly inexpensive, and magnetic data is usually fairly clean, compared to other systems. However, magnetic systems are affected by small amounts of electromagnetic noise as well as the presence of metal devices in the vicinity.

2.1.3 Commercial Systems

Plenty of commercial motion capture systems are available in the market nowadays. The most widely known are APAS (Ariel Dynamics, Inc., Trabuco Canyon, CA, USA), CODA (Charnwood Dynamics Ltd., Leicestershire, UK), ELITE (Bioengineering Technology and Systems, Milano, Italy), OPTOTRAK (Northern Digital, Inc., Waterloo, Ontario, Canada), PEAK (Peak Performance Technologies, Inc., Englewood, CO, USA), QUALISYS (Qualisys Medical AB, Gothenburg, Sweden), VICON (Vicon Motion Systems Ltd., Oxford, UK). (APAS, 2006; CODA, 2006; ELITE, 2006; OPTOTRAK, 2006; PEAK, 2006; QUALISYS, 2006; VICON, 2006). The main features of these video-based motion capture systems are described in the following sections.

2.1.3.1 APAS

The Ariel Performance Analysis System (APAS) is the premier products designed, manufactured, and marketed by Ariel Dynamics, Inc. (APAS, 2006). It is an advanced video-based system taking the advantage of consumer electronic products that are inexpensive and available off-the-shelf. These include standard video cameras, digital video cameras and video cassette recorders for storing image.

The APAS was originally developed around sports and Olympic athletes where markers were not allowed. No special markers are used. While this is an advantage in that the subject is not encumbered in any way, it does mean that the points of interest have to be manually digitized. This tedious procedure leads to a significant amount of time being required, particularly if the user is performing a 3D analysis with multiple cameras and high frame rates. Ariel Dynamics has recently introduced a new motion analysis system, named as APAS-XP, which utilize passive markers for auto-digitizing the video sequences.

APAS system is very flexible, and can be easily moved from one place to another. The video can be recorded almost anywhere using ordinary camcorders. The ability to record the activity as a picture allows the scientist to make intellectual decisions regarding the joint center at each frame rather than using markers attached at the skin's surface. Additionally, up to 32 channels of analog data (i.e. force platform, EMG, goniometers etc.) can be collected and synchronized with the kinematic data.

Although the system has primarily been used for quantification of human activities, it has also been utilized in many industrial, non-human applications. Optional software modules include real-time 3D (6 degree of freedom) rendering capabilities and full gait pattern analysis utilizing all industry standard marker sets.

2.1.3.2 CODA

CODA is an acronym of Cartesian Optoelectronic Dynamic Anthropometer, a name first coined in 1974 to give a working title to an early research instrument developed at Loughborough University, United Kingdom by David Mitchelson and funded by the UK Science Research Council. Today, Coda systems are manufactured by Charnwood Dynamics Ltd. (CODA, 2006).

The CODA mpx30 motion tracking system consists of small infra-red light emitting diodes that are pulsed sequentially, and a camera that incorporates 3 linear sensors. Sampling rates of up to 800 Hz are possible and the system identifies up to 28 targets uniquely and in real-time. Patient encumbrance is minimized by the use of miniature battery packs, each of which has a unique identity so that the Coda system can always recognize the markers. For tracking bilateral movements such as human gait, it is necessary to acquire a second mpx30 system, increasing the cost significantly.

Next generation product of Charnwood Dynamics is the Codamotion system. The system was pre-calibrated for 3D measurement, which means that the lightweight sensor can be set up at a new location in a matter of minutes, without the need to recalibrate using a space-frame. Up to six sensor units can be used together and placed around a capture volume to give extra sets of eyes and maximum redundancy of viewpoint. This enables the Codamotion system to track 360 degree movements which often occur in animation and sports applications. The active markers were always intrinsically identified by virtue of their position in a time multiplexed sequence. Confused or swapped trajectories do not occur with the

Codamotion system, no matter how many markers are used or how close they are to each other.

2.1.3.3 ELITE

ELITE motion analysis system is a product of Bioengineering Technology & Systems (BTS) from Italy (ELITE, 2006). The major components of the ELITE are passive retroreflective markers from 3 to 20 mm diameter; high sensitivity video cameras and either a visible or infrared light source; a computer and software to calibrate, capture, and display the data. Force platform and EMG data may be gathered simultaneously to the kinematic data.

The standard sampling rates are from 50 to 120 FPS (frames per second), and the system accuracy is claimed to be 1/2800 of the view field. Up to eight separate cameras can be used with the video image processor but, as with most video-based systems that use passive markers, the identification of the individual markers still remains a problem that is not entirely handled by the software alone, and some user input is required.

ELITE Clinic is an integrated software package that allows simultaneous collection of kinematics, force plate and EMG data. It utilizes three internationally defined clinical protocols, including the Helen Hayes Hospital marker set, and calculates all the clinically relevant parameters, including segment angles and joint dynamics.

ELITE Biomech Analyzer is based on the latest generation of ELITE systems. It performs a highly accurate reconstruction of any type of movement, on the basis of the principle of shape recognition of passive markers.

3D reconstruction and tracking of markers starting from pre-defined models of protocols are widely validated by the international scientific community. Tracking of markers based on the principle of shape recognition allows the use of the system in extreme conditions of lighting. This system is capable of managing up to 4 force platforms of various brands, and up to 32 EMG channels. It also runs in real time recognition of markers with on-monitor-display during the acquisition, and real time processing of kinematic and analog data.

2.1.3.4 OPTOTRAK

The Optotrak system manufactured by Northern Digital, Inc. utilizes three linear CCDs in a single instrument (OPTOTRAK, 2006). This provides both excellent spatial resolution (claimed to be better than 0.1 mm) as well as high sampling rates (750 Hz for 3 markers). Markers are IR LEDs which are pulsed sequentially so that as the number of markers increases, the sampling rate decreases.

The 3D data are available in real time and unique target identification is achieved, even when a marker disappears from view temporarily. Because the Optotrak instrument is calibrated in the factory, there is no need for calibration in the field prior to data capture. The Optotrak has a field of view of 34º and can track up to 256 markers, thus allowing very detailed motions to be captured. Its disadvantages include subject encumbrance by the trailing cables that strobe the markers and provide power, and only one side of the body can be studied with a single instrument. For tracking bilateral movements such as human gait, it is necessary to acquire a second Optotrak device, increasing the cost significantly.

Northern Digital has recently introduced a cost-effective system called Polaris which is based on two rectangular CCDs. The Polaris system optimally combines simultaneous tracking of both wired and wireless tools. The whole system can be divided into two parts: the position sensors and passive or active markers. The former consist of a couple of cameras that are only sensitive to infrared light. This design is particularly useful when the background lighting is varying and unpredictive.

Passive markers are covered by reflective materials, which are activated by the arrays of IR LEDs surrounding the position sensor lenses. In the meantime, active markers can emit IR light themselves.

The Polaris system is able to provide 6 degrees of freedom motion information. With proper calibration, this system may achieve 0.35 mm RMS accuracy in position measures. However, similar to other marker-based techniques, the Polaris system cannot sort out the occlusion problem due to the existence of the line of sight. Adding extra position sensors possibly mitigates the trouble but also increases computational cost and operational complexity.

2.1.3.5 PEAK

Peak Performance Technologies Inc. was established in Colorado, USA in 1984 with the goal of producing a computer- and video-based biomechanical analysis tool to help athletes improve their performance in preparation for Olympic and world competition (PEAK, 2006).

Peak system consists of the following three options: (1) a two-dimensional system, with video camcorder, video cassette recorder (VCR), video monitor, VCR controller board, personal computer, graphics monitor, printer, and driving software; (2) a three-dimensional system, with additional video cameras that can be synchronized with the master camcorder, a portable VCR, a calibration frame, and appropriate 3D module software; and (3) an automatic system known as Peak Motus, with flood lights, reflective markers, a proprietary hardware interface, and additional software.

The temporal resolution of Peak systems is variable depending on the video recording system being used. The standard system arrangement uses 60 FPS, although the Peak system is compatible with video recording equipment that can record at a rate of up to 200 FPS. The advantages of these systems are as follows: Markers are not always required; movement can be captured on videotape (even under adverse field and lighting conditions) and then processed by the computer at a later time. The major disadvantages are that the video-based systems require considerable effort from the operator to digitize the data, and so the time from capturing the movement of interest to the availability of data can be quite lengthy.

Peak Motus, which can accommodate up to 6 cameras, overcomes this disadvantage when passive retroreflective markers are attached to the subject. An analogue acquisition module enables the user to gather force plate, EMG and other data that are synchronized with the kinematic data.

2.1.3.6 QUALISYS

The heart of the kinematic analysis system from Qualisys is the custom-designed camera, which is called a motion capture unit (MCU) (QUALISYS, 2006). Passive retro-reflective markers are attached to the subject and these are illuminated by infra-red light emitting diodes that surround the lens in the MCU. The light is reflected back to the MCU and the 2D locations of up to 150 targets are calculated in real time.

The ProReflex systems come in two versions, the MCU 240 (operating between 1 and 240 Hz) and the MCU 1000 (operating between 1 and 1000 Hz). Up to 32 MCUs can be connected in a ring-type topology, thus providing complete coverage of any complex 3D movement, including gait. The spatial resolution is claimed to be 1:60000 of the field of view.

Qualisys also supplies the QGait software package which has been designed to integrate kinematic, force plate and EMG data. This includes temporal-distance parameters, as well as 3D angles and moments at the hip, knee and ankle joints.

2.1.3.7 VICON

VICON (the name derives from video-converter) is a product of Vicon Motion Systems that is the successor of Oxford Metrics Ltd. which had been established in Oxford, UK in 1984 (VICON, 2006). Vicon Motion Systems and Peak Performance Technologies Inc. join together very recently under the name of ViconPeak, the result is a combined business that offers an integrated solution for both digital optical and video-based motion tracking.

Vicon 512 system which accommodates up to 12 video cameras is able to track the 3D position of 50 passive targets within a matter of seconds. The cameras, which operate between 50 and 240 Hz, all have a ring of infra-red light emitting diodes surrounding the lens which serve to illuminate passive retro-reflective markers (ranging in size from 4 mm to over 50 mm). The cameras utilize a simplified cabling system, in which the power plus video and synchronization signals are all carried via a single cable to and from the DataStation. The 2D coordinates are transferred from there to the personal computer workstation via 100 Mbit Ethernet.

In addition, 64 channels of analog data such as force plates, EMG and foot switches can be gathered simultaneously. There are two software packages that are designed for the gait analyst: Vicon Clinical Manager (VCM) and BodyBuilder. VCM is specific to gait, and incorporates a patient database, a gait cycles window, and a report generator program called RGEN. BodyBuilder is a general purpose software package which enables the user to customize the biomechanical model to his or her own application.

2.2 C3D File Format

Motion analysis laboratories around the world use several commercial products manufactured by different companies or they use motion analysis systems developed by their own efforts. Therefore, until very recently it was common for the various motion capture systems to store their recorded data in their own unique digital file format.

Because each motion capture system used a different file format, it was virtually impossible to exchange motion data between researchers who have different motion capture systems. Consequently, the motion data file of an experiment recorded with one motion capture system could not be analyzed with a different system, and identical measurements between different systems could not be compared due to differing data and parameter storage methods and assumptions.

Widespread use of C3D file format in many motion analysis systems effectively solved these problems. The design of the C3D data file format was originally driven by the need for a convenient and efficient format to store data collected during biomechanics experiments. The C3D (**C**oordinate **3D**) format stores 3D trajectory and analog data for any measurement trial, together with all associated parameters that describe the data, in a single file.

The C3D file format was developed by Andrew Dainis, Ph.D. in 1987 as a commercial product for the AMASS – ADTech Motion Analysis Software System which was the first commercially available 3D motion measurement software for generating 3D trajectories from digitized video images. The first installation was in the Biomechanics Laboratory at the National Institutes of Health which is one of the world's leading medical research centers located in the United States.

In the late 1980's Oxford Metrics Ltd., obtained distribution rights for the AMASS software from ADTech. In 1992, Oxford Metrics Ltd. developed Vicon Clinical Manager application which uses the ADTech C3D file format as its standard format with a new hardware platform running under Windows operating system. In the early 1990's AMASS was adapted to processing raw video data files generated by several other commercial systems, and was supplied as third party software to a number of motion capture laboratories.

In the course of time, C3D format attracted considerable interest, and its popularity placed the C3D file format in the position that it occupies at the moment. C3D file format is in widespread use throughout the world now, being the most common data file format for biomechanical 3D data, and has become a standard for the storage and exchange of raw 3D and analog data.

Today, most major motion capture systems fully support C3D file format. They can read the data stored in the C3D file format, and they can create data files in this format or they can export their own data into C3D file. Vicon Motion Systems, Motion Analysis Corporation, Motion Lab Systems, Bioengineering Technology & Systems, Charnwood Dynamics, C-Motion, Kaydara, Lambsoft, Peak Performance, Qualisys and Run Technologies are the manufacturers of these C3D compatible systems.

Although the C3D file format has its widest use within clinical gait and biomechanics laboratories, the format is in use in entertainment and animation industry, and supported by several leading animation packages.

The C3D format is not affiliated to any specific manufacturer, and the file specification and format description are freely available at publicly accessible internet web site http://www.c3d.org which is maintained as a resource for all C3D users by Motion Lab Systems Inc., being the developer of a number of software applications that use the C3D file format. The web site hosts a collection of various C3D applications and useful documents that can be downloaded via anonymous ftp service.

The C3D file contains all relevant information for a single trial of data. A typical C3D file usually stores both the positional and analog information regarding one gait trial. Positional information is the reconstructed 3D coordinates which is the marker motion data derived from the camera images. On the other hand, analog information is the digitized data from sources such as EMG and force plate.

In addition to physical measurement data, a C3D file includes parameter information about the data such as measurement units, force plate positions, marker sets and data point labels etc. C3D file format can also store database information such as the subject's name, diagnosis, age at trial, with physical parameters such as weight, leg length etc. C3D file also allows the user to define, generate and store any number custom parameters within the file. Anyone opening the C3D file can easily access all these data from a single file, and this largely eliminates the need for trial data to travel around with additional notes and subject information.

The C3D file is a binary file which is efficient and compact in terms of data storage and access. The C3D format is relatively complex from the programming viewpoint, but in exchange, the format offers the user uniformity and flexibility.

C3D format provides a means of standardizing the interchange of gait trial data, and with the advent of the widespread use of a common data format made it easy for researchers and clinicians to compare information recorded in laboratories with different motion capture systems. Thus, laboratories with different motion capture systems are able to work together, and multiple laboratory collaboration enables to accumulate large samples of gait data and to construct an enhanced clinical gait analysis database.

2.3 EXISTING RESEARCH

In the last two decades, three dimensional motion analysis systems have become widely used in the study of human motion. Reliability of these systems is utmost important, especially when clinical decisions are made, or in research studies. Therefore, a motion analysis system has to be validated through examination of reliability and accuracy of measurements.

There is extensive prior research investigating and evaluating the performance of various motion analysis systems. In these studies, system accuracy and reliability have been determined through system-specific tests. Points of interests were the absolute and relative point estimations, linear and angular estimations, consistency of measurement and static and dynamic accuracy.

Scholz (1989) evaluated the accuracy and the consistency of the Northern Digital's Watsmart system applied to angular and dynamical measurements. Using a standard goniometer, Scholz assessed 12 angles in 5-degree increments from 45° to 100° with two wall mounted cameras positioned 2 m apart, and found that the 95% confidence interval for each angle was less than 0.5° in all cases. Scholz noted that the reliability and accuracy decreased as the object was rotated away from the plane of the cameras.

Linden et al. (1992) reported the accuracy and reproducibility of angular and linear measurements obtained under static and dynamic conditions with the Motion Analysis Expert Vision video system. Vertical plane of the data acquisition region was divided into nine equal sized cells. A rigid wooden bar, to which two spherical reflective markers were attached 178.5 mm apart, was moved randomly in the calibrated field. Using a protocol similar to Scholz (1989), they assessed 17 angles in 10° increments from 20° to 180° with two cameras placed 2.37 m apart, and found that average within trial variability was less than 0.4°.

Scholz and Millford (1993) evaluated the accuracy and precision of the Peak motion analysis system for three-dimensional angle reconstruction. They recorded the pendular motion of a bar with 18 retroreflective markers at three different orientations and found that the average deviation from the actual angle was less than 0.8° across all angles.

Klein and DeHeaven (1995) conducted a series of tests to examine the upper limits of accuracy and consistency of linear and angular measures obtained using Ariel Performance Analysis System. They found that mean 3D linear error estimate was less than 3 mm for a length of 50 cm and mean angular error estimate was less than 0.3° for goniometer settings ranging from 10° to 170°.

Engler et al. (1996) used a fixture consisting four reflective targets rotating about a fixed axis for the assessment of the accuracy of the 6-camera, 120 Hz Vicon 370 movement analysis system.

Jobbágy et al. (1998) investigated the resolution and accuracy of a passive marker-based motion analysis system called PRIMAS developed by Furnée (1989). Jobbágy used a printing head to move a marker horizontally. A straight line was fitted to the measured marker center coordinates and the accuracy is characterized on the basis of the deviations from that line.

Bhimji et al. (2000) assessed the accuracy of Vicon 370 system performing static and dynamic experiments. The three static experiments included the measurements of small, medium and large distances between two markers. Bhimji et al. (2000) conducted a ball drop test and a rotating clock arm test for determining the dynamic accuracy.

It is difficult for users and researchers to compare the performance of various systems from the results of the prior research or from the data supplied by the manufacturers. Because the technical performance of those systems have been measured based on different protocols, relied on generally measurement of a purpose-made fixture, and the tests have been performed under different conditions.

Ehara et al. (1995) conducted a research as an activity of the Working Group for 3D camera system comparison in The Clinical Gait Analysis Forum of Japan (CGAFJ) with the cooperation of manufacturers. This research was intended to measure the performance of commercially available 3D camera systems for clinical gait measurement. For this purpose a protocol was devised from the users' point of view reflecting the requirements of clinical gait analysis in the rehabilitation field. In November 1993, "1st Comparison Meeting on 3D Motion Measuring Systems" was held in Japan. In the meeting, eight different commercial systems were tested under identical conditions, and two of the most important factors, accuracy and processing time were measured according to the proposed protocol. Tested systems were: Quick MAG, Video Locus, Peak 5, Ariel, Vicon 370, Elite, Kinemetrix 3D and Optotrack 3020.

For the accuracy evaluation, relative distances between two markers attached to a rigid bar was measured. The test subject normally walked while holding the bar with his forearm along the torso. There were adhesive tapes stuck on the floor to indicate the direction of walking, and the foot positions that the subject has to be hit with his feet. Measurement was made for 5 seconds with the sampling frequency of 50 or 60 Hz. Finally, measured values were compared with those measured by a scale.

In order to evaluate data processing time, markers were attached to the right side of the test subject at the shoulder, greater trochanter, knee, ankle and the fifth metatarsal joint. The subject walked through the walkway at a normal speed, and was not allowed to swing his arms during walking. After the measurement, the time required for calculating 3D coordinate data and displaying it as a stick figure was measured with a stopwatch. Thus, human interface of the software had also been evaluated. Some systems had a smart marker identification algorithm, whereas some required considerable user intervention.

CGAFJ asserted that there had been advancement or improvement in 3D systems produced by many companies owing to the contributions made by the 1st comparison meeting. Comparison results of the previous research (Ehara et al., 1995) were required to be updated considering the recent developments in terms of both hardware and software of the systems. For this purpose, CGAFJ organized the comparison meetings later in 1995 and 1999.

The methods used for evaluating the measurement accuracy and processing time were basically the same as the previous experiment protocol in the following occasions, but a few experiments were added in order to evaluate the noise. Therefore, the results of all of the above meetings were comparable between each other.

In the comparison meeting held in 1995, 11 commercially available systems were tested, and reported in the paper authored by Ehara et al. (1997). 13 commercial systems were tested to evaluate their performance in the Comparison Meeting '99, and the report had been available via the web for a time.

Later, comparison meeting was held once in 2002, but this time not only the clinical gait analysis systems were evaluated, but also the motion analysis systems used in industry, sports and entertainment. Experiment protocol was designed accordingly, and the results were reported in the Comparison Meeting of Motion Analysis 2002 web site (http://www.ne.jp/asahi/gait/analysis/comparison2002/index-eng.html).

Richards (1999) performed another performance comparison study for the assessment of the clinical performance characteristics of seven optical-based and one electromagnetic-based biomechanical measurement system. He used a testing device that systematically moved the seven markers within the calibration volume. Two markers were placed 50 cm apart on top of a rigid aluminum bar that rotated in the horizontal plane at a rate of approximately 60 rpm. Three markers were placed in a triangular pattern on a plate mounted vertically at the end of the bar. The plate was perpendicular to the bar, and the markers were placed on the outside surface. A sixth marker was mounted to the base of the device on a 3-cm rigid post. The final marker was mounted to a post on the bottom of the rotating bar, and at the same height as the stationary base mounted marker. The position of the marker below the bar was adjustable along the length of the bar so that the minimum distance between the stationary marker and the orbiting adjustable marker could be controlled.

Six trials were collected with the variable and stationary markers separated by distances of 5, 4, 3, 2, 1, and 0 cm, respectively. Deviations from known distances between fixed markers and deviations from known angles were determined for each of the systems measured.

Hassan, Jenkyn and Dunning (2006) calculated the dynamic accuracy of kinematic data measured by a digital optical motion analysis system compared to a standard range direct-current electromagnetic (EM) tracking device. Rigid clusters of spherical reflective markers and EM sensors were affixed to a mechanical articulator that mimicked three-dimensional joint rotations, similar to the elbow. As the articulator was moved through known ranges of motion, kinematic data were collected simultaneously using both tracking systems.

All of the above presented comparison studies evaluated the data acquisition performance of the systems, through the analyses of accuracy of static and/or dynamic points, distances, and/or angles. However, different commercial motion analysis systems use different gait models and these models use different calculations to determine the joint center locations, segment orientations, and three dimensional joint angles and moments. Therefore, the kinematic results of the systems have to be assessed for the comparison of different gait analysis methodologies.

Besser et al. (1996) determined the criterion reference validity of the APAS and GaitLab software systems for the calculation of lower extremity joint angles. In this study, left lower extremity of a plastic skeleton was fixed in various positions using clamps and rods. Kinematic data were collected with APAS, the images from each videotape were digitized and 3D marker locations were constructed using direct linear transformation. The marker data were then analyzed with both APAS and GaitLab to calculate the joint angles. They examined the total error associated with joint angle calculations using these two different motion analysis systems.

Woledge, Delaney, Thornton and Shortland (2005) compared the normal data between two clinical gait analysis laboratories. One set of normal data for 12 children was collected using Coda equipment and software and the other set was for 17 children obtained from Vicon motion analysis system. Woledge et al. (2005) analyzed the normal data in two aspects which they defined as position and movement. Position is the value through the gait cycle and movement is the difference between signal at a time and the position, namely the mean value. They found that the movements recorded by the two laboratories were very similar, whereas the positions were statistically different. In other words, trends of the normal data between two gait analysis laboratories were the same but there existed shifts.

Mannon et al. (1997) compared two dimensional rearfoot motion during walking measured by a traditional video-based motion analysis system to that of an electromagnetic analysis system. A set of data from twenty-five subjects was evaluated, and a high correlation between the mean motion paths produced by the two systems was found.

Rainbow et al. (2003) compared the results of two different gait analysis software packages, namely VCM and Visual3D. In this retrospective study, a single stride was analyzed in both VCM and V3D for each of 25 patients. Paired t-tests were used to detect differences in means for 20 variables commonly used to make clinical decisions. Results showed no statistical difference between the Helen Hayes modeling in VCM and V3D for 16 out of 20 variables. The variables showing a significant difference were four out of six joint moments tested, specifically, max knee extension moment in late swing, max ankle plantar flexion moment, max hip abduction moment in early stance, and max hip extension moment in early stance.

In the above three studies, the gait data from a certain number of subjects were collected with two different motion analysis systems, and then the kinematic results were statistically analyzed and compared. However, natural variability exists in the gait of people and can be attributed to many factors including age, height, and walking speed. Thus, such an approach is not sufficient to compare the analysis software of the systems directly.

Gorton, Hebert and Goode (2001) evaluated the kinematic results of one test subject at 12 Shriners Motion Analysis Laboratories. Ten of 12 laboratories employed Vicon Motion analysis equipment and the remaining two utilized Motion Analysis Corporation hardware and software. The variability due to differences between sites, between clinicians, and by the subject within a test session is examined. Additionally, system accuracy and the variability of the test subject within and between test days are investigated. Gorton et al. (2001) found out that all systems produced reliable results under controllable conditions. Results were differing between test sessions by different clinicians within and among sites. The lowest variability was noted for the angles that did not require careful alignment of wands and did not depend upon joint center calculation. Gorton et al. (2001) suggested that the predominant source of variability is due to marker placement differences among clinicians between sites.

To study the same subject on each system would be an approach for the comparison of the systems, however, normal trial to trial variability and other possible error factors related to the performer and the laboratory conditions could not be avoided in the experiments. To obtain a more reliable comparison, two different approaches were proposed in the literature. One of these two approaches is the simultaneous data collection and the other one is analyzing the same set of data on different systems.

Polak, Attfield and Wallace (1996) compared the acquisition performance characteristics of two motion analysis systems during simultaneous real time data collection in order to facilitate data exchange for a multi-centre study. A four CCTV camera Elite system which tracks passive infrared illuminated markers collected data simultaneously, with the Codampx30 system, having three cameras, tracking active infrared markers. A hemispherical passive Elite marker was placed directly over the centre of the Coda LED marker, with a central hole to allow the infra-red light to remain visible. The combined marker, named as ELCO marker, enabled the simultaneous data acquisition in the same working environment. A simple biomechanical model was used, four markers were attached the subject unilaterally at greater trochanter, knee, ankle and fifth metatarsal head. The subject walked through the acquisition volume of both systems, and the Cartesian coordinates of both systems were aligned with the use of an offset marker. The coordinate data were taken into an excel spreadsheet, and synchronized by SPSS statistical software time series auto correlation. Both sets of coordinate systems for a single stride of data were analyzed by one software package in order to calculate relative joint angles of knee and ankle. Results showed that there were no significant differences between both systems in the sagittal plane angles.

Polak and Attfield (1997) used the same approach of the study of Polak et al. (1996). They statistically compared the x, y and z coordinates of the four markers obtained by 3D reconstruction software from each system. They determined some major differences between the systems. The deviations in the line of progression in the laboratory (x-coordinate data) showed consistent negative results, whereas the deviations in the y and z plane consistently showed positive results for the mean difference across all the four markers. However, further computation of the raw data showed that the derived knee and ankle motion had a high degree of correlation in the sagittal plane. Polak and Attfield explained this significant difference such that one of the systems exhibited a slight drifting in calibration parameters.

Moraes, Silva and Battistela (2003) compared the two different kinematic analysis software packages for the same set of data. They used the 3D motion capture system called Eva Hires (Motion Analysis Corporation, Santa Rosa, CA, USA). The system could operate with either Ortho Trak or Kin Trak which were installed at the laboratory. Both Ortho Trak and Kin Trak are the data analysis software packages developed by the same manufacturer, Motion Analysis Corporation, however, the results obtained were not the same. Moraes et al. (2003) evaluated the movements of bending, squatting and sitting down as well as the normal walking in their study. Moraes et al. (2003) stated that they had expected some differences due to the precision of joint center calculation in each software package, but they thought that there would not be such large deviations such as the ones observed in the trunk angle.

There are many data analysis software packages manufactured by different companies in the market, and they generally store their data in their native file format. Thus, collected data from one system can not be read directly by the other system’s programs, and file conversion procedures are required at this time.

Rash, Quesada, Butsch and Augsburger (2000) investigated whether or not there were any significant differences between the calculated kinematics of the two gait analysis programs, AutoGait by Qualisys and OrthoTrak by Motion Analysis Corporation. They performed an experiment, and obtained the coordinate data in the Qualisys system. AutoGait software was used to compute the joint angles of the subject’s right leg. Excel macros were then used to convert the coordinate data that could be read by OrthoTrak for data analysis.

Kinematic results obtained from both software packages were then plotted on the same graph for one gait cycle. Kinematic results were found to be very comparable for most of the plots. Plots of the rotation angles had the greatest difference; the ankle plots were not fair as well. Inversion angles were not even close.

Kirtley and Kranzl (2000) tested the modeling software of the two different systems, Vicon by Oxford Metrics Ltd. and ExpertVision by Motion Analysis Corporation (MAC) by taking the advantage of that both systems support the common C3D data format. They evaluated the two systems using two different models.

Vicon Clinical Manager (VCM), which is the software responsible for performing modeling calculations of the Vicon system, uses the Modified Helen Hayes Model, developed by Davis et al. (1991). This model can also be used by MAC system software, OrthoTrak. Additionally, Oxford Metrics Ltd. has recently introduced the BodyBuilder (BB), which is a flexible kinematic and kinetic modeling tool enabling the creation of completely custom models. Hence, the Modified Helen Hayes Model was able to be compared in three different gait analysis software packages, VCM, BB and MAC.

The second model compared was Cleveland model, which uses marker clusters on the thigh and shank segments. The Cleveland Clinic Marker set is a proprietary marker set own by Motion Analysis Corporation. MAC OrthoTrak model was constructed in the BodyBuilder, and finally the kinematic results were obtained by both MAC and BB.

Results showed that there were no noticeable differences in the kinematics when Modified Helen Hayes Model was used. In the kinetics, there were slight differences only in the hip and knee power curves between MAC and Vicon (both VCM and BB). Cleveland-type model yielded very similar results in the kinematics and power. There were minor differences in some of the kinetic variables, particularly the hip moment during early stance.

Tabakin and Vaughan (2000) compared three gait analysis models [Vicon Clinical Manager (VCM), GaitLab 2.0 (GL) and Peak Motus 2000 (PM)] with a standard model developed using the Vicon BodyBuilder (BB) software package.

VCM, GL and PM; they all use the Helen Hayes marker set, however the methods for calculating the joint center locations and segment orientations, as well as the net joint forces and moments differ. VCM software uses methods described by Kadaba et al. (1990) and by Davis et al. (1991), while GL and PM use methods described by Vaughan et al. (1992).

Gait analysis was performed on 20 subjects, from a wide range of heights and body masses. The gait experiments were performed using Vicon 6-camera motion analysis system. The identical kinematic data were then processed using VCM, GL and PM gait analysis software packages, as well as the BodyBuilder model.

The BodyBuilder model was used as the standard by which the three commercial software packages could be compared. For each parameter, the absolute difference was calculated between BB and the model at each of 51 time increments (0% to 100% in 2% steps) and the average of these 51 points for all 20 subjects was then calculated.

The results showed a significant difference between BB and VCM for the plantar/dorsi flexion angle of the ankle and the abduction/adduction angles of the hip and knee. Authors believed that these differences were arisen from the different algorithms used to define the segment axes and joint centers. Significant differences are also noted in the hip, knee and ankle flexion/extension moments (BB vs VCM and BB vs PM). These differences are assumed to be a result of the different methods of estimating joint centers as well as body segment parameters.

CHAPTER 3

KISS VERSUS VICON:

A GENERAL COMPARISON

The Biomechanics Laboratory at the Mechanical Engineering Department of Middle East Technical University is the first gait analysis laboratory in Turkey, and is being used for research and clinical purposes. The laboratory is currently increasing its research profile both by researchers within the Mechanical Engineering Department, and in collaboration with other related disciplines in METU and clinical people from other universities. Clinically, the laboratory provides a gait analysis service to Ankara, accepting referrals from locally agreed physiatrists without charge.

METU – Biomechanics Laboratory has developed her own data acquisition and analysis software for the quantification of human movement. This locally developed system has been established using off-the-shelf equipment, and is called **KISS**, which is the acronym of "**K**as **İs**kelet **S**istemi" in Turkish and "**Ki**nematic **S**upport **S**ystem" in English.

On the other hand, the Clinical Gait Analysis Laboratory at Ankara University Medical School Department of Physical Medicine and Rehabilitation was established in 1997, and over 2500 subjects referred by physiatrists, orthopaedic surgeons and sports medicine physicians from all over the country have been analyzed up to now. The laboratory is equipped with a commercial **VICON 370^{TM}** motion capture system manufactured by Oxford Metrics Ltd.

METU-KISS and Ankara University – VICON gait analysis systems were compared in this thesis in terms of the data acquisition performance and model based data analysis methodology.

3.1 SYSTEM DESCRIPTION

3.1.1 Laboratory Arrangement

Gait analysis laboratories in METU and Ankara University have similar physical conditions and equipments. Both laboratories have rectangular shape rooms large enough for the subjects to walk up easily and to be able to inhouse the multiple tripod-mounted cameras surrounding the walkway.

General views of the METU-Biomechanics Laboratory and the Ankara University Clinical Gait Analysis Laboratory are shown in Figure 3.1 and Figure 3.2, respectively.

Figure 3.1 Biomechanics Laboratory in METU

Figure 3.2 Clinical Gait Analysis Laboratory in Ankara University

Biomechanics Laboratory in METU has dimensions of 6 m x 10 m x 3 m (width, length and height). 0.8 meters wide and 4.6 meters long area along with the laboratory floor has been designed as walkway. Two force plates have been embedded within the floor, and the walkway has been covered with the same color as the force plates, but different from the surrounding area.

Clinical Gait Analysis Laboratory in Ankara University has dimensions of 5 m x 12 m x 3 m (width, length and height). Gait analyses are performed over a walking platform having a length of 7 meters and width of 2 meters. The height of the platform is 10 cm.

3.1.2 Hardware

The hardware of both systems consists of three main parts:

- Force measurement
- Electromyography
- Motion capture

3.1.2.1 Force Measurement Unit

Both laboratories use the same type of force plates 4060 HT manufactured by Bertec (Bertec Corporation, Columbus, OH, USA). Two staggered force plates located in the centre of the walkway allows to measure ground reaction force resultants along three orthogonal axes and moment resultants around these axes when a subject walks across it. Dimensions of the force plates are 40 cm x 60 cm and their measurement range is between 0 – 2 kN.

Both systems employ two 6-channel amplifiers of type AM6-3 (Bertec Corporation, Columbus, OH, USA) with an output of ±10 V and stepwise adjustable gains of 1, 5, 10, 20, 50, and 100 are used to amplify the voltage output of the force plates.

3.1.2.2 Electromyography (EMG) Unit

The KISS system uses an 8-channel EMG of type Octopus AMT-8 (Bortec Biomedical Ltd., Alberta, Canada) for recording the muscle activity during gait, whereas Ankara University Clinical Gait Analysis Laboratory is equipped with a 6-channel dynamic EMG (Motion Lab Systems, Inc., Baton Rouge, LA, USA).

If muscle activation levels are needed to be known, a set of surface electrodes is placed on the skin overlying the relevant muscles of the subject for EMG measurements. The primary disadvantage of this technique is the cumbersome nature of the instrument. Normal pattern of the walking might be affected by the electrodes attached on the subject; therefore, only one or two trials are realized with EMG electrodes.

3.1.2.3 Motion Capture Equipment

The KISS motion capture system is equipped with six tripod-mounted CCD cameras (Ikegami Electronics, Inc., Maywood, NJ, USA) surrounding the walkway. Vicon 370 system can accommodate up to 7 cameras, however there are five standard Vicon cameras employed in the Ankara University – VICON gait analysis system. Camera arrangements within each laboratory are illustrated in Figure 3.3 and 3.4.

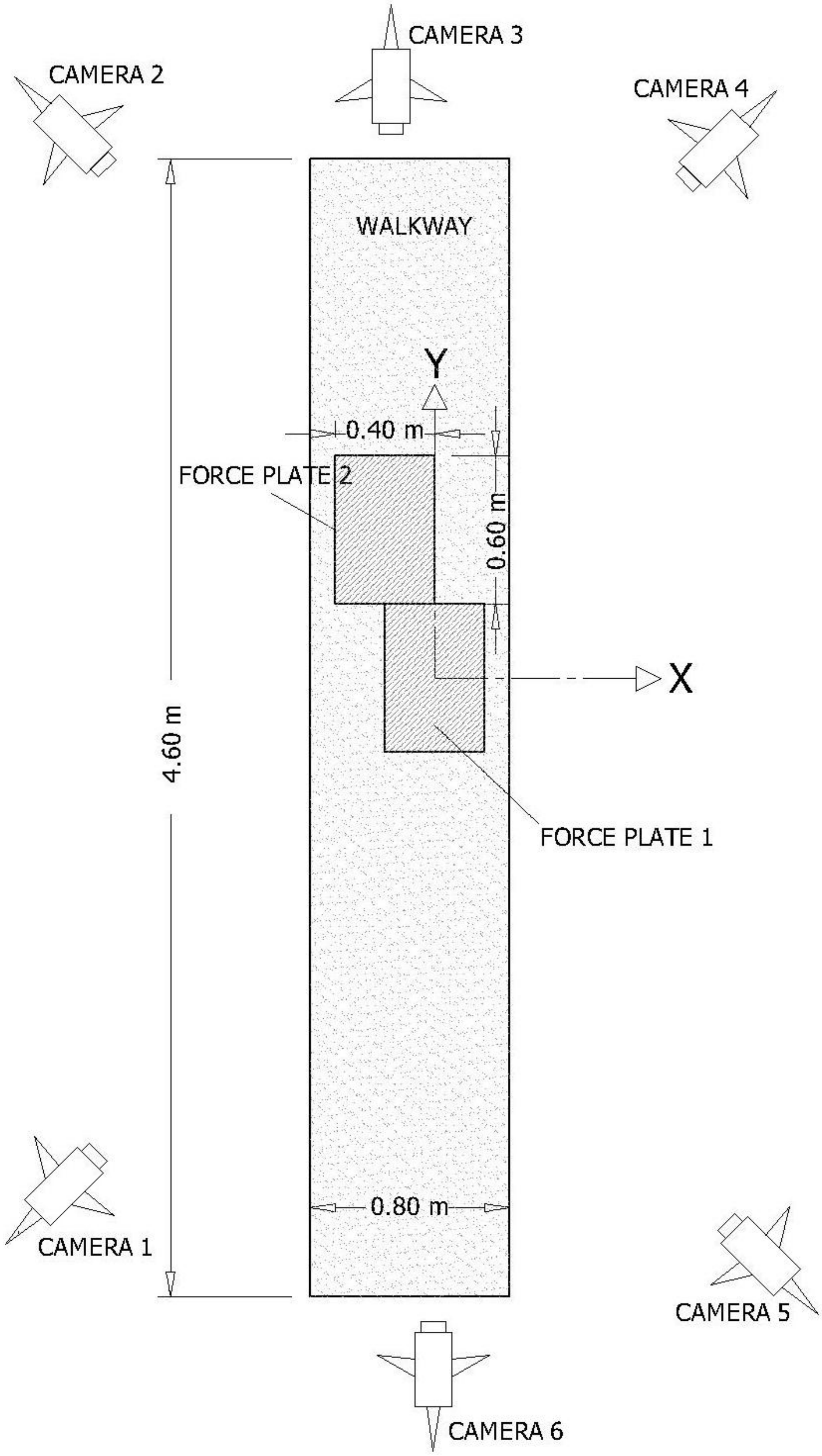


Figure 3.3 Camera Arrangements in KISS System (Top view)

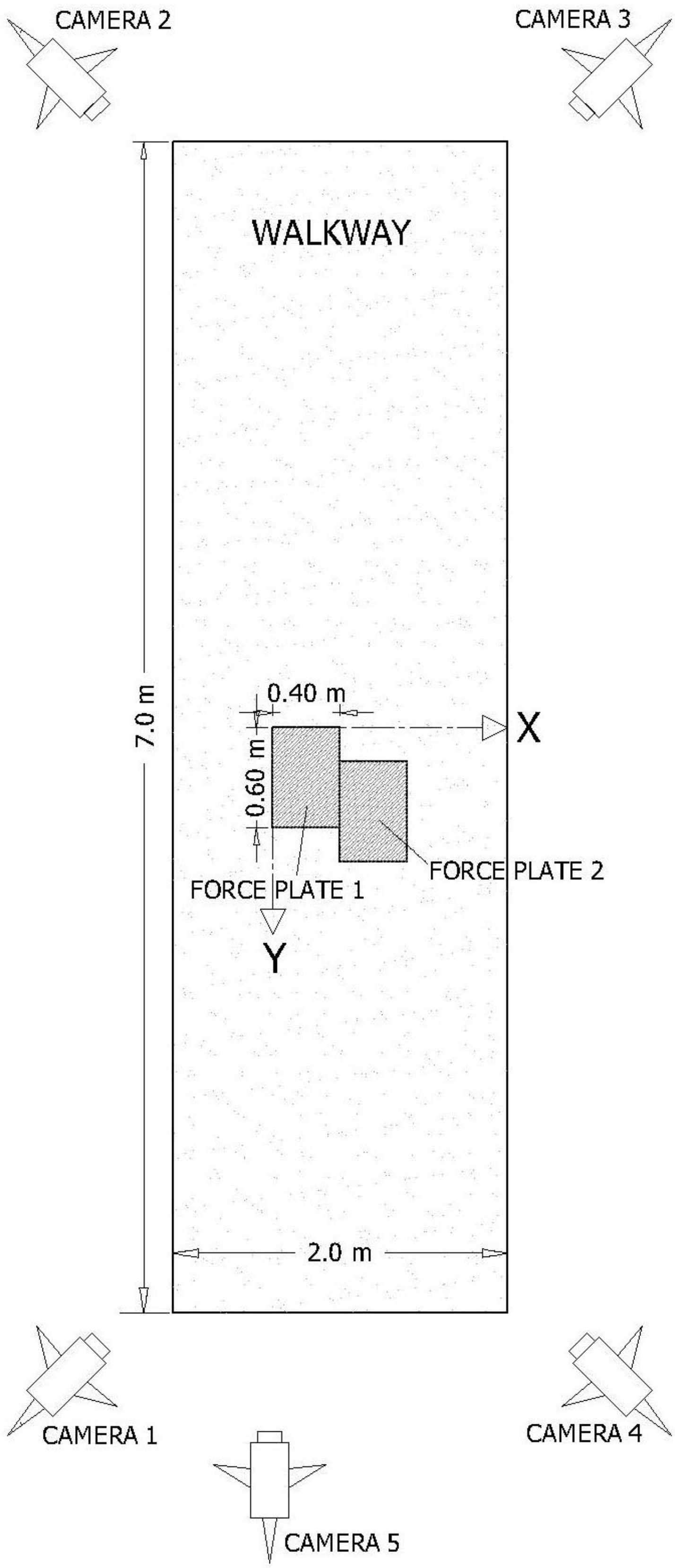
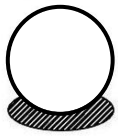
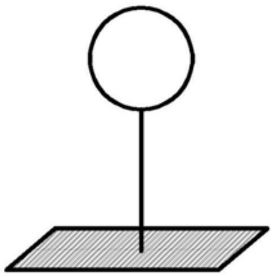
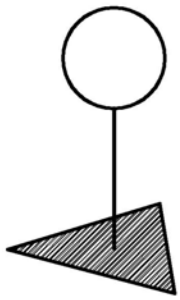
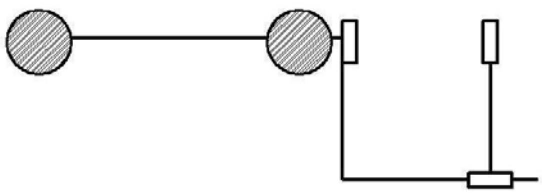


Figure 3.4 Camera Arrangements in VICON System (Top view)

Markers used in both systems are one inch (approx. 25 mm) diameter spheres, manufactured from wood, and covered with 3M® retroreflective material that reflects infrared light. Infrared strobes have been mounted around the camera lenses with infrared pass filters so that the infrared light emitted by the strobes is reflected back from markers, and identified by the cameras. Both systems record the kinematic data at a sampling rate of 50 Hz.

In KISS protocol, marker balls are applied directly on the skin with a circular base, or a wand or rod is used with markers attached to the endpoints. These types of markers are called stick markers or wand markers. There are also specially designed knee and ankle centering devices used in the static shot according to KISS protocol. Types of markers that are used in KISS protocol are illustrated in Table 3.1.

Table 3.1 Type of markers used in KISS system

1	Marker on a circular base	
2	Marker on a 40 mm rod with rectangular base	
3	Marker on a 40 mm rod with triangular base	
4	Vise-like devices having two markers attached at a distance (Knee and Ankle Centering Devices)	

In the regular experiments conducted in Ankara University – VICON system, only surface markers are placed on the anatomical landmarks. However, stick markers and knee alignment device can be used optionally.

When markers are directly attached to some anatomical locations, they may not sometimes be visible by at least two cameras because of arm swings, etc. (occlusion). Stick markers are used to overcome this problem, since they allow the markers to be located at a short distance away from the body. Furthermore, they prevent the three markers that characterize each segment to be collinear in order to avoid kinematic singularities. They also provide more accurate orientation of the segment in 3-D space.

In spite of the advantages, stick markers encumber the subject, and if he or she has a jerky gait, or suffers obesity the sticks vibrate and move relative to the underlying skeleton.

In KISS, the video output of each camera is fed into Vidmux (video-multiplexer, Odessa Inc., Ankara, Turkey) where the images are digitized and multiplexed, and a frame grabber card is used to transfer these images to the memory of the host computer. The force plate and EMG signals are also sampled synchronously along with the camera images by an Analog to Digital (A/D) converter card (National Instruments, Austin, TX, USA).

The VICON 370 system has two main physical parts. The first, data station contains 7-channel video converter and a 32-channel analog to digital converter for data acquisition. The second, workstation consists of a personal computer (450 MHz Pentium II), running Microsoft Windows 98.

Both systems have a linearization grid to correct the lens distortion errors and camera calibration apparatus in order to estimate the calibration parameters to be used in 3D reconstruction.

3.1.3 Software

Software of KISS system is comprised of two main programs called Kiss-DAQ and Kiss-GAIT. The data acquisition software, Kiss-DAQ records and stores image data synchronously with force plate and EMG measurements, and then processes the data for pixel grouping and marker identification, and finally reconstructs the three-dimensional marker trajectories. This software also used to perform camera linearization and calibration. After data recording, assigning and labeling of the marker trajectories are carried out by a motion analyst using the program called *tracks.exe*. An intermediate software called *pkbvd.exe* combines the 3D tracks, force plate and EMG data together in a single file.

The second software, Kiss-GAIT takes the combined file as input, and performs the calculation and presentation of gait parameters. Kiss-GAIT enables the motion analyst to define the gait cycle by identifying basic gait events such that the heel strike and toe off for each leg and then utilizes a biomechanical model to compute the joint angles, joint moments and powers, as well as temporal and spatial parameters.

On the other hand, VICON system has Vicon 370™ Version 2.6 as data collection software and Vicon Clinical Manager (VCM) for gait analyses whose algorithm is hidden in the software.

Vicon 370 ™ software resides in both the data station and workstation. A single interactive program on the workstation controls data capture and upload, 3D photogrammetric calibration and fully-automatic 3D reconstruction, and display of results. The Vicon 370™ generates the source data for gait analysis program called as VCM, which utilizes inverse dynamics to solve the equations of motion needed to determine the kinematic and kinetic variables. Excel based macros are used to calculate the outcome gait parameters.

3.2 DATA COLLECTION PROTOCOL

3.2.1 Calibration of the Cameras

An accurate calibration is important for reconstructing the 3D trajectories from the 2D image data. For this reason, cameras should be calibrated daily after each time the system is switched on. Calibration of the cameras are performed by using a set of control points for which the three dimensional coordinates in a laboratory fixed coordinate system are known.

In KISS system, four high precision calibration rods of length 2 meters are used as the calibration apparatus (Figure 3.5). Six retroreflective markers have been rigidly attached in a unique configuration on each rod as control points, so that a particular rod can be automatically recognized.

Figure 3.5 KISS-Calibration Rods

Before any experiment, calibration rods are suspended from the ceiling of the laboratory to enclose the calibration volume, which is a region of space common to the field of view of all cameras. The levels of the rods are adjusted by the surveyor's telescope, by measuring the vertical components of the control markers relative to a control line precisely drawn on the laboratory wall. Calibration volume of KISS system is 1.6 m x 3 m x 1.5 m (width, length and height). Volume length allows one full stride length for a normal adult subject, and the volume width is limited with the width of the force plates.

Before starting the calibration task, it is required to extinguish the oscillations of the vertically hanging rods as much as possible. Then, each camera view should be inspected in order to verify if there are any unwanted reflections. If there are, their source should be detected and removed.

The calibration apparatus of VICON system consists of two parts: a calibration object for the static calibration and a wand for dynamic calibration.

The static calibration object is an L-frame, with leg lengths of 464 mm and 508 mm, comprising four accurately spaced markers attached on the legs. The device is designed for placement over a force plate, where the edge of the corner piece (the object origin) will accurately align with the edge of the plate (Figure 3.6).

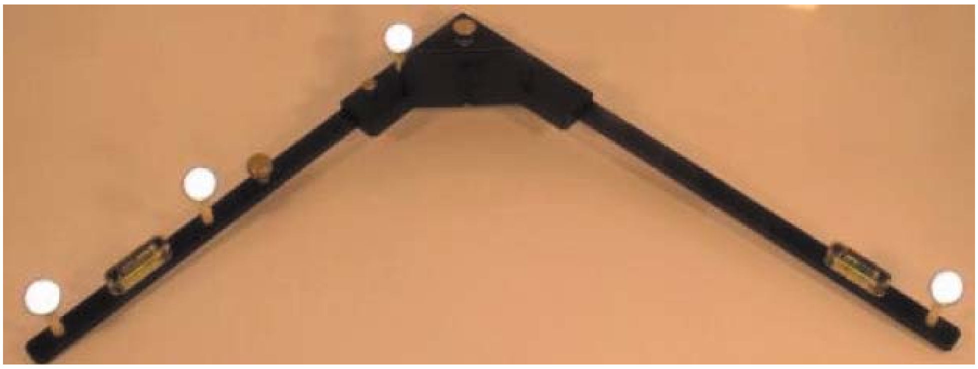


Figure 3.6 Static Calibration Object used in VICON system

The origin and the axes of the laboratory fixed coordinate frame are defined by the position of the L-frame. Before conducting the experiment, L-frame is positioned on the force platform. Then static calibration task is initiated, and the data is captured for 20 frames duration and stops automatically.

The wand consists of two 50.8 mm retroreflective marker balls, placed on a rod with their centers 500 mm apart. A handle is placed on the other end of the rod for the operator (Figure 3.7).

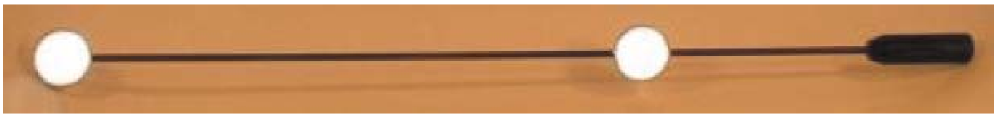


Figure 3.7 Dynamic Calibration Wand used in VICON system

After static calibration of the cameras, L-frame is removed and wand is prepared for capturing the calibration space, which is 5 m x 7 m x 2.1 m (width, length and height). The act of dynamic calibration involves moving throughout the capture volume, waving the wand so that it passes through as much of the calibration volume as possible allowing each camera to record the wand in several orientations. After capturing, Vicon 370 calculates the calibration residuals, which are preferred to be around 1 mm. If they are greater than 2 mm, the calibration has to be performed again.

3.2.2 Linearization of the Cameras

Both KISS and VICON systems utilize a linearization grid shown in Figure 3.8 to correct the lens distortion errors in the camera images. A perfect 15 x 20 grid is formed with circular points of diameter 1 cm using retroreflective material.

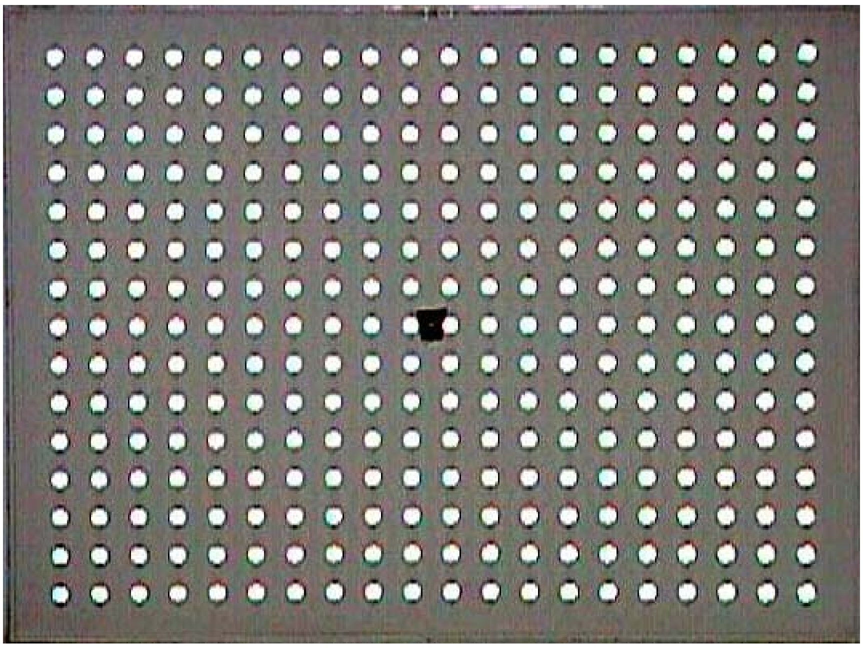


Figure 3.8 Linearization Grid

The linearization algorithm to correct for lens distortion errors is based on finding a mapping between the distorted image and the perfect grid. The first step is the formation of an arbitrary primary grid. Then, a perfect grid, which is closest to the distorted grid, is computed using least squares technique. Next, using the corresponding grid points 4^{th} order polynomials are formed to transform the image coordinates of the distorted grid to the image coordinates of the perfect grid.

3.2.3 Anthropometric Measurements

Certain anthropometric measurements are required to be obtained via direct measurement on the subject to calculate the segment masses and moments of inertias. These include height and weight of the subject, the leg lengths, knee and ankle widths for each leg, the distance between right and left pelvis anterior superior iliac spine (ASIS).

Leg length is measured from the anterior superior iliac spine to the medial malleolus through medial epicondyle for each leg. Knee width is the distance measured between lateral and medial epicondyles, and ankle width is the distance between lateral and medial malleoli.

In VCM model, there is no need to measure the distance between right and left ASIS, since this can be obtained from coordinate data of the markers attached on the both ASIS. However, Vicon 370 allows the user to enter inter-ASIS distance as an optional feature. In some patients, particularly those who are obese, the markers either cannot be fixed exactly over the spines, or are invisible in this position to cameras. In such cases, the true inter-ASIS distance must be measured manually, and then be entered on the session form.

Because anthropometric measurements largely affect gait kinematics and kinetics data, precise measurement of body segments is very important. For kinematic data, error of anthropometric data will produce inaccuracies in joint center estimations and the determination of the link coordinate systems.

3.2.4 Marker Configuration and Placement

In both KISS and VICON systems, experimental procedure is comprised of two stages. First stage is the static trial, and second stage is the gait trials that follow the static trial.

3.2.4.1 Gait Trial

Both KISS and VCM protocol use thirteen markers in gait trial in order to track the motion of the seven lower extremity body segments, which are thigh, shank, and foot on both the left and right sides, and the pelvis.

Markers are attached to the body according to the Helen Hayes Hospital marker set developed by Kadaba et al. (1990). Specific anatomical locations defined in this marker set are listed in Table 3.2 with corresponding labels assigned to each marker in KISS and VICON systems.

Table 3.2 Marker Set used in gait trials of both KISS and VICON systems

Marker No.	Label in KISS	Label in VICON	ANATOMICAL LOCATION
1	SACRUM	SACR	Middle of posterior superior iliac spine
2	RASIS	RASI	Right pelvis anterior superior iliac spine
3	LASIS	LASI	Left pelvis anterior superior iliac spine
4	RTHIGH	RTHI	Right thigh
5	LTHIGH	LTHI	Left thigh
6	RKNEE	RKNE	Right lateral epicondyle of the femur
7	LKNEE	LKNE	Left lateral epicondyle of the femur
8	RSHANK	RTIB	Right shank
9	LSHANK	LTIB	Left shank
10	RANKLE	RANK	Right lateral malleolus
11	LANKLE	LANK	Left lateral malleolus
12	RMETA2	RTOE	Right second metatarsal
13	LMETA2	LTOE	Left second metatarsal

Figure 3.9 and 3.10 illustrate Helen Hayes Hospital marker set that uses stick type of markers. Anatomical locations over which markers are attached can be seen in these figures by considering the marker numbers listed in Table 3.2.

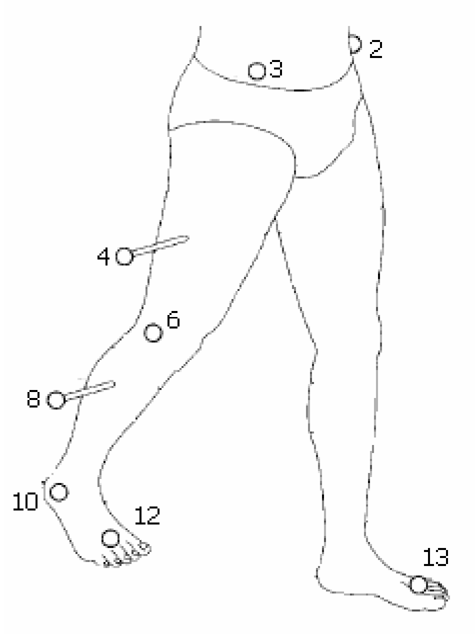


Figure 3.9 Markers used in Gait Trial
(Anterior view)

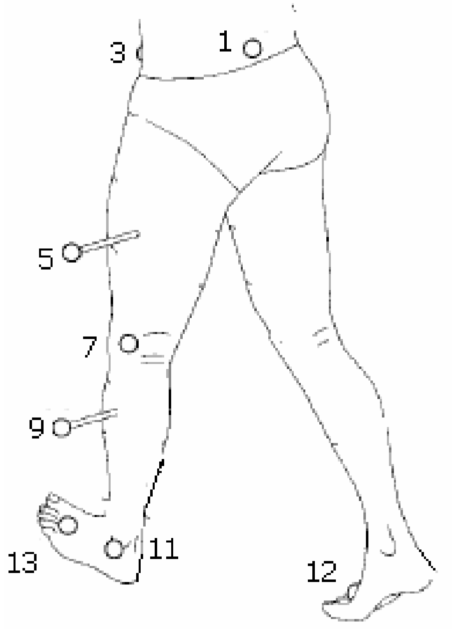


Figure 3.10 Markers used in Gait Trial
(Posterior view)

(Adapted from *Dynamics of Human Gait*, by C. L. Vaughan, B. L. Davis, J. C. O'Connor, 1999, Cape Town: Kiboho Publishers)

To place markers on the exact position is critically important in gait analysis, since the incorrect placement of the markers is probably the largest source of error for instrumental gait analysis, and more important is that it is unpredictable. Kirtley (2002) performed a study in order to record the kinematic and kinetic consequences of deliberately incorrect marker attachment.

The following describes in detail where the Helen Hayes markers should be placed on the subject. The positioning is identical for both the left and right side.

Pelvic markers (right and left ASIS) should be placed directly over the spines while the subject is standing, since the skin over the ASIS is highly mobile. Sacrum marker is attached mid-way between the skin dimples formed by the posterior superior iliac spines. These are slight bony prominences which can be felt immediately below the dimples (sacro-iliac joints), at the point where the spine joints the pelvis. In KISS protocol, a stick marker with a triangular base is attached on the sacrum with a double-sided adhesive tape.

The most reliable way to achieve good placement of the knee marker is to stand the patient on the opposite foot, and ask the patient to flex and extend the knee passively through 40-50 degrees while watching the skin surface on the lateral aspect of the knee joint. While the subject is moving his or her leg, the experimenter should specify the point, which comes closest to stationary in the thigh. This landmark should also be the point about which the lower leg appears to rotate. If this point is marked by a pen, with an adult patient standing, this pen mark should be about 1.5 cm above the joint line, mid-way between the front and back of the joint. Knee marker is then placed over the point.

According to VCM protocol, thigh marker is placed on the leg over the lower lateral one third surface of the thigh, just below the swing of the hand. Although the height is not so critical, this prevents the occlusion of markers due to arm swings. In VCM protocol, antero-posterior placement of the marker is critical for correct alignment of the knee flexion axis. The thigh marker needs to be positioned so that it is aligned in the plane that contains the hip and knee joint centers and the knee flexion/extension axis. This is not a simple process and may require some practice to achieve repeatable results. In order to make the process simpler, a mirror placed on the wall several meters away from the subject may be utilized. Then, the operator places his or her finger on the greater trochanter, where the hip joint lies under it for healthy individuals. Afterwards, thigh marker is adjusted until it forms a straight line with the finger and knee joint marker.

In KISS protocol, placement of the thigh marker is not critical; stick marker with a rectangular base can be placed, theoretically, anywhere on the thigh segment.

The ankle marker is placed over the bony prominence of the lateral malleolus along an imaginary line that passes through the transmalleolar axis.

Similar to the thigh markers, shank markers are placed over the lower one third of the shank apart from ankle to determine the alignment of the ankle flexion axis according to VCM protocol. The shank marker should lie in the plane that contains the knee and ankle joint centers and the ankle flexion/extension axis.

Placement of the shank markers is not critical as well according to the KISS protocol, stick marker with a rectangular base can be placed anywhere on the thigh segment.

The forefoot markers are placed on the dorsal surface of the foot over the second metatarsal head, on the mid-foot side of the equinus break between the forefoot and mid-foot in both protocols. The subject can be asked to flex the toes in order to facilitate identification.

3.2.4.2 Static Trial

In the first stage of the experiment, namely in the static shot 19 markers are used in KISS protocol, whereas, VCM protocol uses 15 markers. Additional markers that are used in static trial are listed in Table 3.3.

Table 3.3 Markers used in Static Trial different from Gait Trial

KISS	**VICON**	**ANATOMICAL LOCATION**
RHEEL	RHEE	Right heel
LHEEL	LHEE	Left heel
ROKCD	-	Right Outer Knee Centering Device
RIKCD	-	Right Inner Knee Centering Device
LOKCD	-	Left Outer Knee Centering Device
LIKCD	-	Left Inner Knee Centering Device
ROACD	-	Right Outer Ankle Centering Device
RIACD	-	Right Inner Ankle Centering Device
LOACD	-	Left Outer Ankle Centering Device
LIACD	-	Left Inner Knee Centering Device

Heel markers are essential for static analysis according to both protocols. Heel marker is placed on the calcaneus at the same height above the plantar surface of the foot as the forefoot marker on the second metatarsal head, that is the line between heel and forefoot markers should be parallel to the ground.

In the static shot record, specially designed vise-like centering devices are required to be attached on the knees and ankles according to the KISS protocol. Knee and ankle centering devices having two markers at a distance on a rigid rod, are placed on the knees and ankles, respectively in such a way that the line defined by these two markers pass through the respective joint centers.

Although there is knee alignment device in VCM protocol, the use of this device is encouraged but left optional. In Ankara University Clinical Gait Analysis Laboratory knee alignment device is not used in the experiments.

Static trial with additional markers over anatomical landmarks is performed to define segment coordinate systems and marker locations within those coordinate systems. A static trial is captured before the gait trials. The subject stands stationary in the center of the walkway in natural upright stance position and data is collected for a period of one second.

After the static trial is collected, heel markers are removed from the subject and now the subject is ready for the gait trial in VCM protocol. In KISS protocol, besides heel markers, knee and ankle centering devices are also removed and instead knee and ankle markers are attached.

Prior to gait trials, the subject is instructed to move forward, walking at his or her normal pace. Some warm-up walking trials can be performed in order to find the preferred pace and best starting point to walk. The subject must complete at least one and a half stride within the calibration volume in a gait trial; otherwise the data cannot be analyzed. If the kinetic analysis will be conducted, the subject's each foot must step on only one force plate at a time.

After all necessary adjustments, as patient walks several times gait data is captured for a period of 5-10 seconds for a number of gait trials. Gait trials involving proper foot placement on the force plates are chosen for processing in the kinematic analysis software.

3.3 DATA REDUCTION PROTOCOL

3.3.1 Preliminary Considerations

3.3.1.1 Anatomical Terms of Motion

In human anatomy, specific directional terms are used to describe movements of the body. These terms always use anatomical position as a point of reference, even if the structure or body described is in another position. Anatomical position together with the reference planes and the directional terms are illustrated in Figure 3.11.

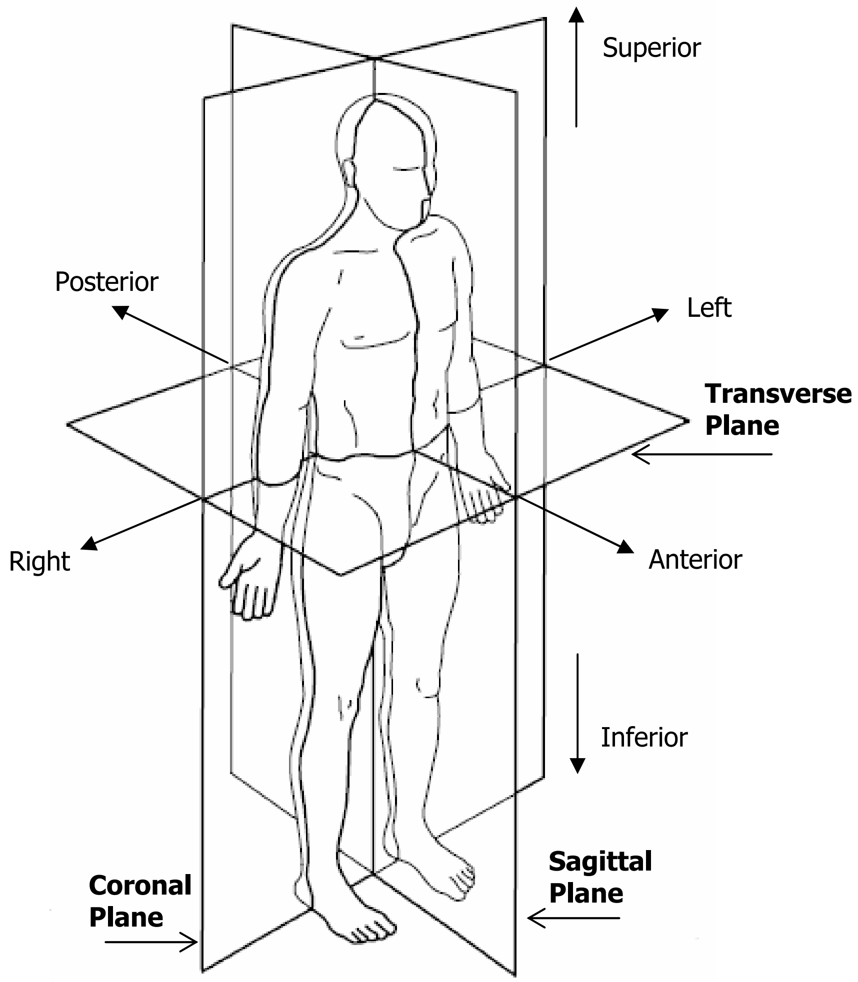


Figure 3.11 Anatomical Position, with three reference planes and six fundamental directions (Adapted from *Human Walking*, by V. T. Inman et al., 1981, Baltimore: Williams & Wilkins)

Anterior means toward the front of the body, while *posterior* means the back of the body. The term *superior* means toward the head or the upper part of a structure while *inferior* refers to the lower part of a structure or away from the head. *Proximal* means closer to the trunk while *distal* is away from the trunk. *Medial* describes a structure toward the midline of the body and *lateral* away from that midline.

Anatomists divide body into planes to facilitate discussion. These are sagittal, coronal and transverse planes. *Sagittal* plane is the vertical plane that passes through the midline and divides body into (equal) right and left portions. *Coronal* plane, also named as frontal plane is the vertical plane that passes through the midline and divides the body into anterior and posterior portions; perpendicular to the sagittal plane. *Transverse* or horizontal plane is parallel to the ground and perpendicular to the sagittal and frontal planes, and divides the body into superior and inferior portions.

The body has a wide variety of movements, depending on the joint where the movement occurs. Flexion and extension take place in the sagittal plane. *Flexion* is the movement that decreases the angle between two parts, while *extension* is a straightening movement that increases the angle between body parts. Flexion and extension of the ankle are *dorsiflexion* and *plantar flexion*, respectively. Abduction and adduction are the motions in the coronal plane. *Abduction (valgus)* is movement away from the body, and *adduction (varus)* is movement toward the body; the reference here is the midsagittal plane of the body. Motions which take place in transverse plane are internal and external rotations. *External (or lateral) rotation* occurs when the anterior surface rotates outward and *internal (or medial) rotation* occurs when it rotates inward. Inversion is the inward rotation of the sole of the foot, while eversion is the outward rotation of the foot.

3.3.1.2 Reference Frames

Two different types of Cartesian reference frames are used in motion analysis systems for discussing human motion. There is a global frame of reference, which divides the laboratory volume into 3 planes. The location and orientation of body segments in space are expressed with respect to that global reference frame. And also, each body segment has a local frame of references, which describes body segments with respect to each other. By convention, movement of the distal segment is discussed with respect to the proximal segment.

Local reference frame, also named as body-fixed coordinate system, is a Cartesian coordinate system fixed on a moving rigid body. To define the link coordinate system of a rigid body, 3D positions, with respect to global coordinate system, of at least three non-collinear points should be known. Without defining the local coordinate system, 3D movement of a rigid body cannot be described in 6 DOF.

Wu and Cavanagh (1995) from Standardization and Terminology Committee (STC) of the International Society of Biomechanics (ISB) made the recommendation to define the conventions for X, Y and Z axes of global reference frame. According to Wu and Cavanagh, X coincides with the walking direction assigned to the subject and points anteriorly. Y is orthogonal to the floor and points upwards. Z goes from the left to the right-hand side of the subject.

Grood and Suntay (1983) had proposed a Joint Coordinate System (JCS) for knee as a standard convention. To adapt this method to the other joints, Wu and Cavanagh (1995) have proposed to start by defining a local coordinate system for each segment (Segment Coordinate System – SCS).

According to this convention recommended by Wu and Cavanagh (1995), x axis of SCS represents anterior, y represents proximal, and z is defined from x and y using right hand rule. Cappozzo, Catani, Croce and Leardini (1995) also defined right handed anatomical frames for the pelvis and lower limb segments and proposed these for standardization.

Wu et al. (2002) then defined joint coordinate systems based on the SCS definitions. JCS for various joints follow the similar procedures as proposed by Grood and Suntay (1983). First, a cartesian SCS is established for each of the two adjacent body segments. Secondly, a JCS is established based on the two SCSs. Hence, joint motion including three rotational components, is defined based on the JCS.

Two of the JCS axes are body fixed and these axes are embedded in proximal and distal segments whose relative motion is to be described. One of the JCS axes is the common perpendicular to the two body-fixed axes, and is called the floating axis. The floating axis is fixed to neither of the bodies, and moves in relation to both.

3.3.1.3 Anatomical Landmarks

One of the problems in capturing kinematic data is that gait analysis is really interested in the position of the underlying skeleton, however only the positions of external landmarks can be measured. Markers that are attached onto the external landmarks are called technical markers.

Technical markers can be traced by cameras but they are not sufficient to define the coordinate frames from which anatomically meaningful joint angles can be estimated. Therefore, a larger set of reference points, called anatomical landmarks (AL), is required.

ALs are either palpable bony prominences (external landmarks) or they are identifiable from X-rays (internal landmarks). Internal landmarks can be estimated using prediction approach or virtually generated from technical markers and/or static shot calculations. Prediction approach uses regression equations whose coefficients were obtained by using imaging techniques. Anthropometric measurements are used in these regression equations as independent variables.

Both the anatomical and technical coordinate systems for each link are computed in the static trial, and the mathematical relationship between the anatomical and technical coordinate systems is fixed during gait, since links are assumed to be rigid.

As Söylemez (2002) pointed out that static shot is performed to find a constant transformation between surface-marker-defined coordinate system (technical coordinate system) and inside-body-marker-defined coordinate system (anatomical coordinate system).

3.3.2 Global Coordinate System Definitions

Data acquisition software of the systems, namely Kiss-DAQ and Vicon 370 estimate the marker coordinates with respect to a global coordinate system, also called as laboratory-fixed reference frame. Global coordinate systems of Kiss-DAQ and VICON are different from each other as shown in Figure 3.12 and 3.13.

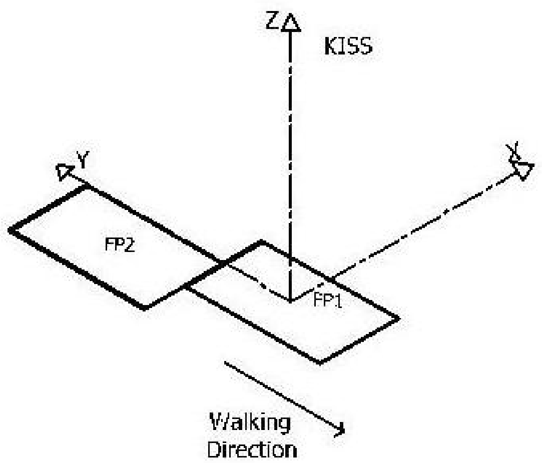


Figure 3.12
Global Coordinate System of KISS

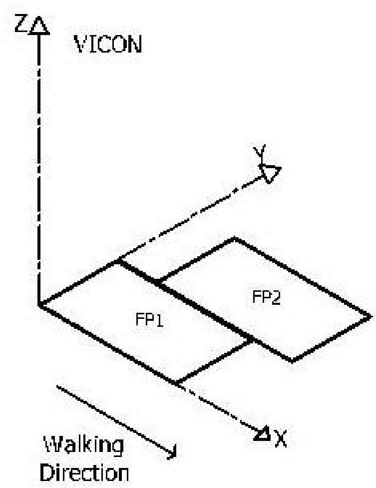
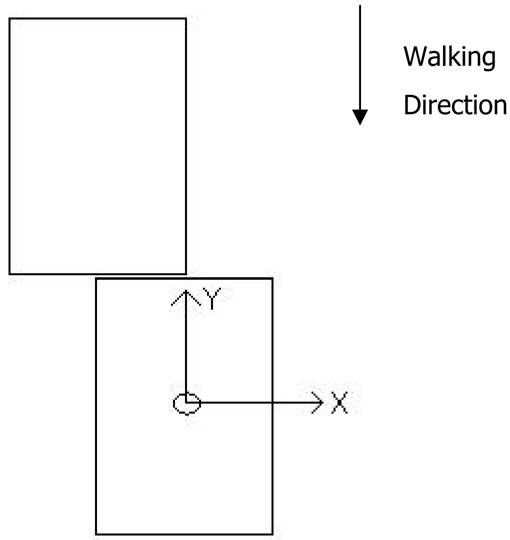


Figure 3.13
Global Coordinate System of VICON

In Kiss-DAQ, three dimensional positions of all markers are expressed with respect to a reference frame whose origin is in the centre of the first force plate, and negative Y axis of the reference frame represents the walking direction. On the other hand, in VICON system, origin of the reference frame is located in the corner of the first force plate, and direction of travel is denoted by X axis.

The important point to notice is that there exist two different laboratory fixed coordinate systems defined in KISS system. Data acquisition software Kiss-DAQ reconstructs the 3D marker coordinates in the frame as shown in Figure 3.12 and 3.14. Whereas, data analysis software Kiss-GAIT uses the reference coordinate system shown in Figure 3.15 to define and calculate variables in joint kinematics.



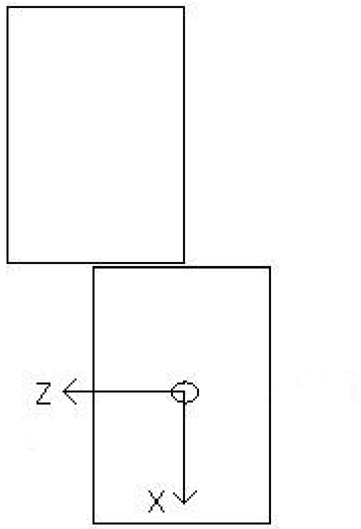


Figure 3.14
Global Coordinate System of Kiss-DAQ

Figure 3.15
Global Coordinate System of Kiss-GAIT

Global Coordinate System of Kiss-GAIT conforms to the definition made by International Society of Biomechanics for standardization of gait data, which has been mentioned in Section 3.3.1.2 of this thesis.

VICON system uses the global coordinate system shown in Figure 3.13 not only for 3D coordinate reconstruction but also for the calculation of joint kinematics.

3.3.3 Kinematic Model

Both KISS and VICON systems utilize the same kinematic model to compute the joint angles. The lower limb is modeled as a sequence of four rigid links connected by three spherical joints. Each link in this model represents one of the segments of the leg those are pelvis, thigh, shank and foot, and the three joints represent the hip, knee and ankle joints (Figure 3.16).

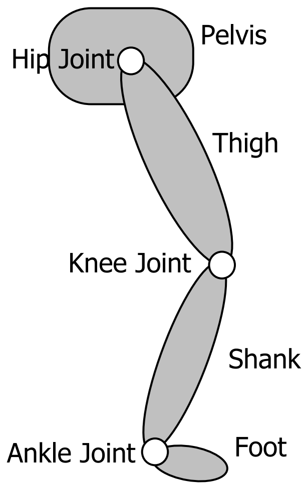


Figure 3.16 Biomechanical Model of the leg

This kinematic model assumes that the dimensions of rigid segments and their segment parameters do not change during the motion of interest, and does not allow for tissue deformation and joint translations.

Each joint is modeled as a sequence of three single axis rotational joints as shown in Figure 3.17, thus leading to the lower limb a total of 12 degrees of freedom.

Mechanical joint model given in the Figure 3.17 is utilized in the calculation of joint angles in both KISS and VICON systems. This model describes the relative motion of distal segment frame with respect to the proximal segment frame. Table 3.4 shows three joints of the lower extremity and the relevant distal and proximal segments.

Table 3.4 Lower Extremity Joints and Relevant Segments

JOINT	**PROXIMAL SEGMENT**	**DISTAL SEGMENT**
Hip	Pelvis	Thigh
Knee	Thigh	Shank
Ankle	Shank	Foot

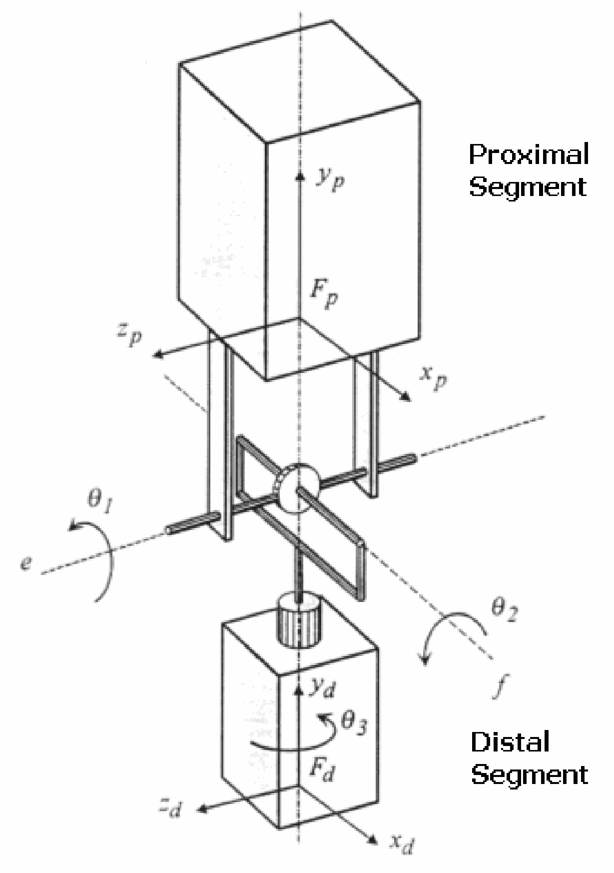


Figure 3.17 Mechanical Joint Model used in Gait Analysis

Figures 3.18 illustrate the kinematic model used in Kiss-GAIT. Black filled circles on the figure are the technical markers placed in dynamic trials, and hatched circles represent the markers placed in static shot only. Empty circles show the anatomical landmarks virtually generated from technical markers. They are midpoint between ASIS markers, and hip, knee and ankle joint centers (HJC, KJC, AJC).

Figure 3.19 illustrate VCM kinematic model. Big circles on the figure show technical markers placed in dynamic trials, and small circles show the anatomical landmarks except technical markers.

Local coordinate frames for each segment can also be seen in Figures 3.18 and 3.19. Kiss-GAIT uses the same kinematic model as VCM as far as the hierarchical structure and the joint types of the model are concerned. However, there exist slight differences in joint center estimation methods and local coordinate system definitions, which will be further presented in Sections 3.3.4 and 3.3.5, respectively.

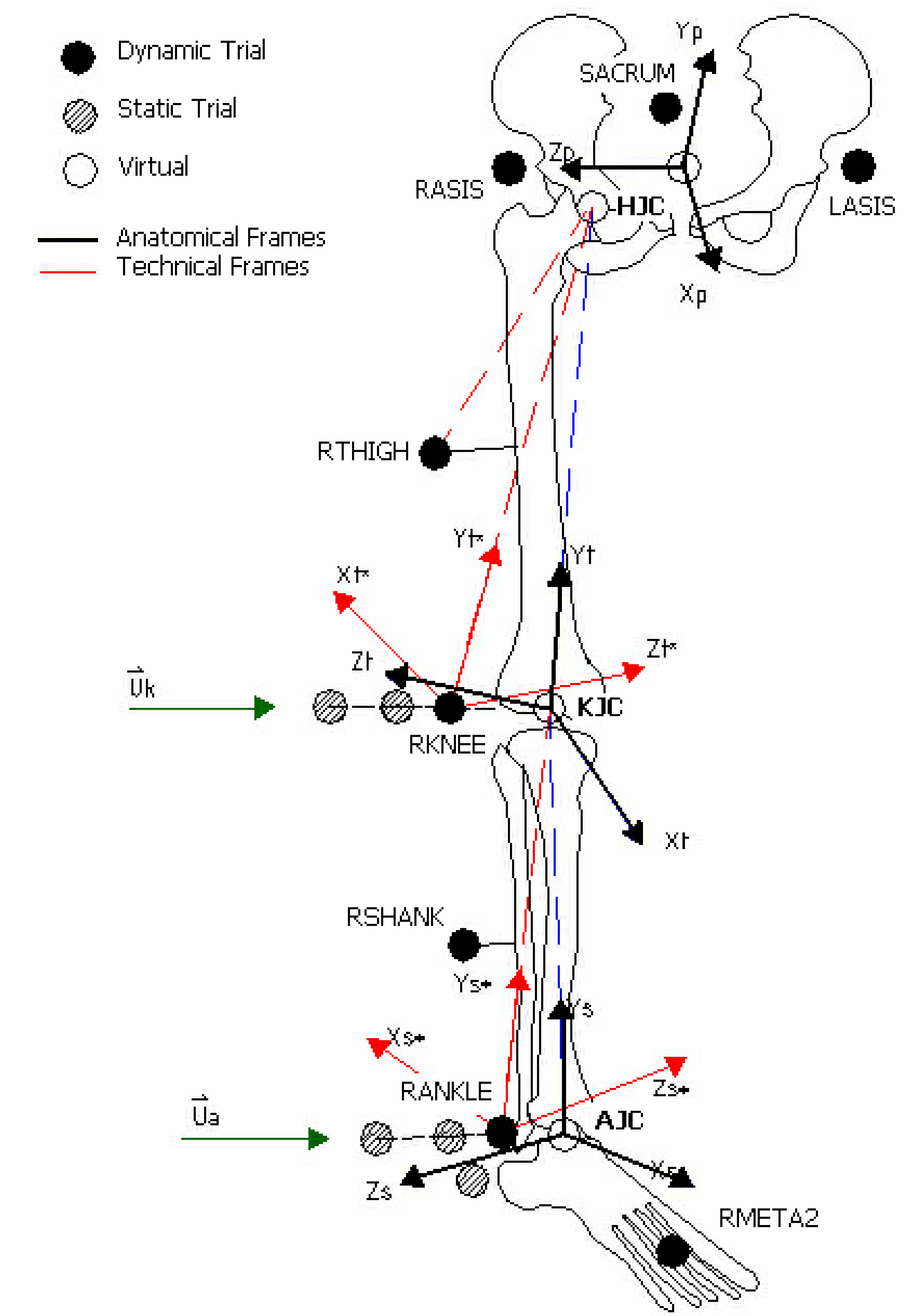


Figure 3.18 Kiss-GAIT Kinematic Model

(Adapted from *An investigation on the gait analysis protocol of the KISS Motion Analysis System,* by Burcu Söylemez, 2002)

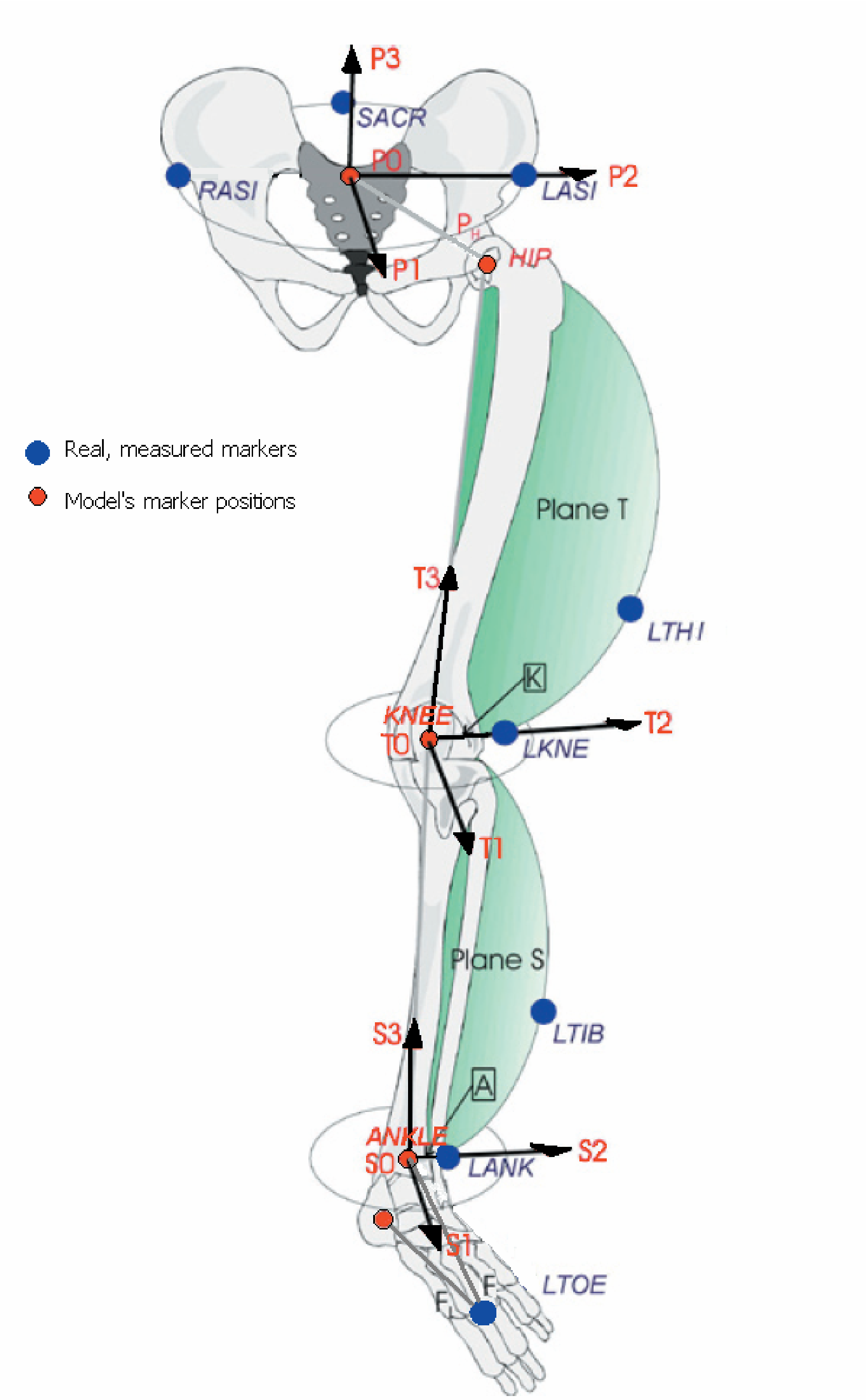


Figure 3.19 VCM Kinematic Model

(Adapted from *White Paper: OLGA Explained*, by Lasse Roren, Retrieved August 14, 2006 from http://www.vicon.com/products/documents/WP_olga_06.pdf)

3.3.4 Joint Center Estimations

3.3.4.1 Hip Joint Center

Joint centers are required to be estimated for the calculation of anatomically meaningful joint angles. Certain assumptions are made in the use of kinematic modeling to determine joint centers. Both Kiss-GAIT and VCM are able to calculate the location of the hip joint center (HJC) from the positions of pelvic markers by using a regression equation developed by Davis et al. (1991) through radiographic examination of 25 hip studies.

Location of the HJC relative to the origin of the pelvis embedded coordinate system in pelvic coordinates is defined as in the following equations.

$$X_H = -(x_{dis} + r_m)\cos\beta + C\cos\theta\sin\beta \tag{3.1}$$

$$Y_H = -(x_{dis} + r_m)\sin\beta + C\cos\theta\cos\beta \tag{3.2}$$

$$Z_H = -\sigma\left[C\sin\theta - \frac{d_{ASIS}}{2}\right] \tag{3.3}$$

where:

$$C = 0.115 \cdot L_{leg} - 15.3 \tag{3.4}$$

L_{leg} = leg length (in millimeters)

x_{dis} = ASIS to trochanter distance

r_m = marker radius (in millimeters)

d_{ASIS} = inter-ASIS distance

θ = 28.4°

β = 18°

σ = +1 for the right side, and -1 for the left side

For KISS, leg length is the length of either the right or left leg depending on which HJC location is to be estimated, whereas VCM averages the leg lengths.

In Davis's method, ASIS to trochanter distance (x_{dis}) need to be measured (anterior/posterior component of the ASIS-hip center distance in the sagittal plane of the pelvis) during the clinical examination.

If ASIS to trochanter distance had been measured and entered to the session form, VCM use Davis's method. Otherwise, an alternative method developed by Bell, Brand and Pedersen (1990) is used for the HJC estimation. Since ASIS to trochanter distance were not measured in the experiments carried out in this study, VCM use the method of Bell et al. (1990).

According to this method, the HJC is located from ASIS by certain distances defined by the percentages of Inter-ASIS distance. Bell et al. (1990) determined these percentages through radiographs of 31 normal adult skeleton pelves. As a result, the HJC was located from ASIS by 19% of the inter-ASIS distance posterior, 30% distal and 14% medial.

In KISS protocol, ASIS to trochanter distance is calculated directly by the linear regression Equation 3.5, even it is not measured.

$$x_{dis} = 0.1288 \cdot L_{leg} - 48.56 \tag{3.5}$$

Finally, the HJC is calculated by using the Equation 3.6.

$$\vec{r}_{HJC} = \vec{r}_{PELC} + X_H \vec{i}_P + Y_H \vec{j}_P + Z_H \vec{k}_P \tag{3.6}$$

where:

$\vec{r}_{PELC}$ = pelvic center position vector defined by the mid point of two ASIS markers

In VCM protocol, locations of Y_H and Z_H in Equation 3.6 are interchanged; since the local coordinate system definitions are differ from each other.

3.3.4.2 Knee and Ankle Joint Centers

The knee and ankle joint centers are determined relative to the positions of the existing markers during the static shot. In Kiss-GAIT protocol, the knee joint center

(KJC) is estimated based on the coronal plane knee width measurement obtained during the clinical examination, that is, the location of the KJC in thigh coordinates and relative to the lateral knee marker is calculated by the Equation 3.7.

$$\vec{r}_{KJC} = \vec{r}_{KNEE_{virtual}} + \left[r_m + 0.5w_{knee}\right] \cdot \vec{u}_k \tag{3.7}$$

where:

r_m = marker radius

w_{knee} = knee width

$\vec{u}_k$ = unit vector along the knee flexion axis

The unit vector along the flexion axis of rotation for knee is found using the markers in static shot (cross-hatched markers in Figure 3.20). It is defined from outer knee centering device marker (labeled as OKCD) to inner knee centering device marker (IKCD).

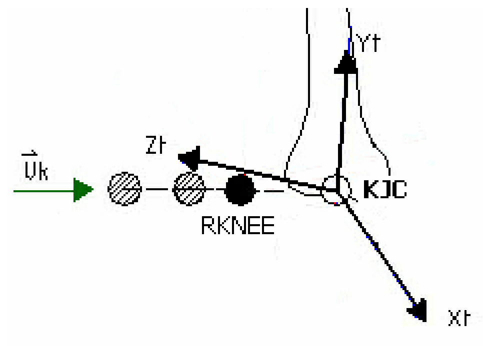


Figure 3.20 Unit vector along the knee flexion axis

Since the motion data for the KNEE marker is collected in dynamic trials, for the calculation of thigh coordinate axes from the static shot, the virtual knee marker $KNEE_{virtual}$ is required to be generated, and its position is found by the Equation 3.8.

$$\vec{r}_{KNEE_{virtual}} = \vec{r}_{IKCD} + KCDO \cdot \vec{u}_k \tag{3.8}$$

where:

$\vec{r}_{IKCD}$ = inner knee centering device marker in static shot

$KCDO$ = knee centering device offset; is the distance between IKCD in static shot and the knee marker labeled as KNEE in dynamic test.

The location of the ankle joint center (AJC) estimation employs the same way that is used for the knee joint center estimation.

$$\vec{r}_{AJC} = \vec{r}_{ANKLE_{virtual}} + \left[r_m + 0.5w_{ankle}\right] \cdot \vec{u}_a \tag{3.9}$$

where:

$$\vec{r}_{ANKLE_{virtual}} = \vec{r}_{IACD} + ACDO \cdot \vec{u}_a \tag{3.10}$$

r_m = marker radius

w_{ankle} = ankle width

$\vec{r}_{IACD}$ = inner knee centering device marker in static shot

$ACDO$ = ankle centering device offset, that is the distance between inner ankle centering device marker (IACD) in static shot and the ankle marker (ANKLE) during gait trials.

$\vec{u}_a$ = unit vector along the flexion axis of ankle, defined from outer ankle centering device marker (OACD) to inner ankle centering device marker (IACD) (Figure 3.21).

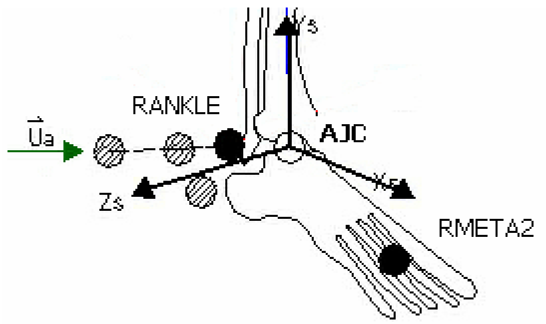


Figure 3.21 Unit vector along the ankle flexion axis

In VCM protocol, knee and ankle joint centers are estimated by the help of the "CHORD" function.

$$CHORD\ (Number\ A,\ Point\ I,\ Point\ J,\ Point\ K) \tag{3.11}$$

Function 3.11 determines the point at distance A from I in plane IJK forming a right angle between I and J on the opposite side of IJ from K (Figure 3.22).

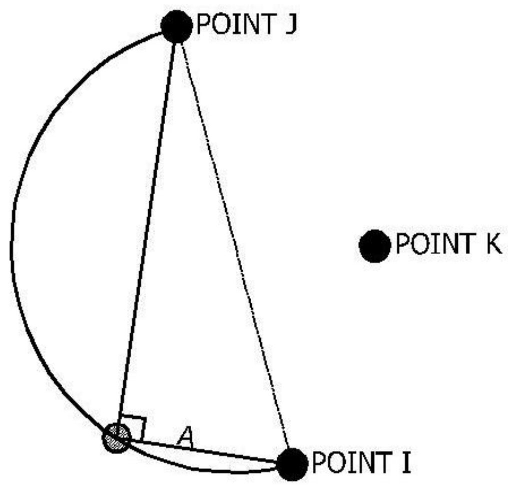


Figure 3.22 Schematic representation of "CHORD" function

KJCs positioned at the thigh's distal end are defined by the HJCs located by a regression Equation 3.6, the lateral thigh markers (LTHI/RTHI) and the lateral knee markers (LKNE/RKNE).

$$KJC = CHORD\ (KneeOS,\ KNE,\ HJC,\ THI) \tag{3.12}$$

where

$$KneeOS = (Marker\ Diameter + Knee\ Width)/2 \tag{3.13}$$

CHORD function simply draws an arc based on the calculated hip joint center and passing through the knee marker and thigh marker. It then draws a chord through this arc at the knee marker, which is the computed knee joint axis. Halfway along this will be the center.

AJCs are defined by the KJCs, the lateral shank markers (LTIB/RTIB) and the lateral ankle markers (LANK/RANK).

$$AJC = CHORD\ (AnkleOS,\ ANK,\ KJC,\ TIB) \tag{3.14}$$

where

$$AnkleOS = (Marker\ Diameter + Ankle\ Width)/2 \tag{3.15}$$

3.3.5 Local Coordinate System Definitions

Local coordinate systems are defined using at least three anatomical landmarks, which create a plane passing through the segment. The spatial position and orientation of each segment are described by a set of segment axes. The joint angles are then calculated from the absolute and relative orientations of the segment axes.

Anatomical reference frames for the body segments used in Kiss-GAIT and VCM are explained in the following.

Illustrations in Figure 3.23 and 3.24 represent pelvic coordinate systems of Kiss-GAIT and VCM, respectively.

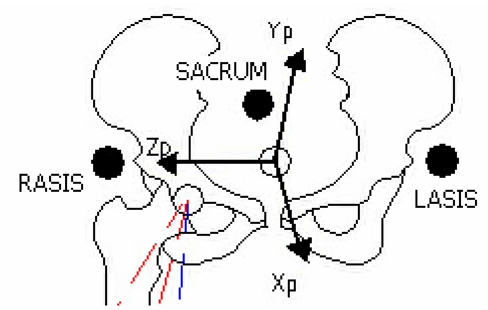


Figure 3.23
Kiss-GAIT – Pelvic Coordinate System

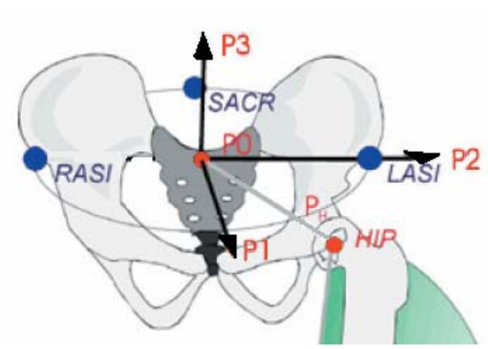


Figure 3.24
VCM – Pelvic Coordinate System

Kiss-GAIT – Pelvic Coordinate System

O_p – The origin is at the midpoint between two ASIS markers.

Z_p – The Z axis is oriented as the line passing through the ASISs with its positive direction from left to right.

Y_p – The Y axis is orthogonal to the plane defined by RASIS, LASIS and SACRUM and its positive direction is superior.

X_p – The X axis is perpendicular to other two axes.

VCM – Pelvic Coordinate System

P0 – The pelvic origin is the midpoint along the first axis, between markers RASI and LASI.

P2 – The first axis is oriented as the line passing through the ASISs with its positive direction from right to left.

P1 – The second axis lies in the plane formed by the markers LASI, RASI and SACR, forming a right angle with the first axis at the pelvic origin.

P3 – The third axis is perpendicular to the first and second.

Anatomical coordinate systems for right and left thigh used in Kiss-GAIT and VCM are given in Figure 3.25 and 3.26.

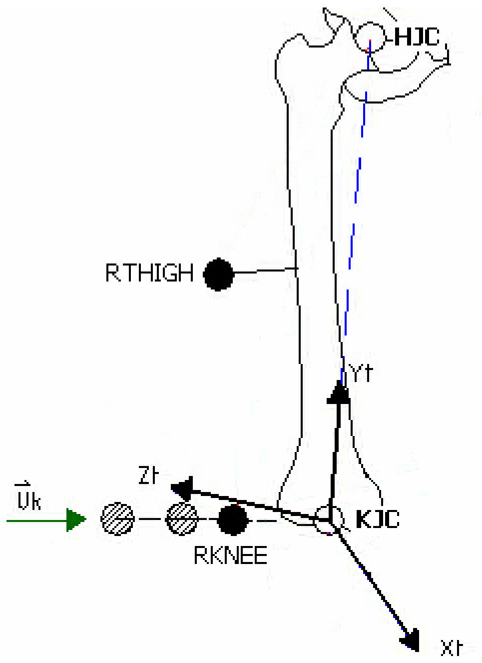
Kiss-GAIT – Thigh Coordinate System

O_t – The origin is located at estimated KJC.

Y_t – The Y axis joins the origin with the HJC and its positive direction is proximal.

X_t – The X axis is orthogonal to the plane defined by HJC, KJC and $\vec{u}_k$ (knee axis) and its positive direction is anterior.

Z_t – The Z axis is perpendicular to other two axes.



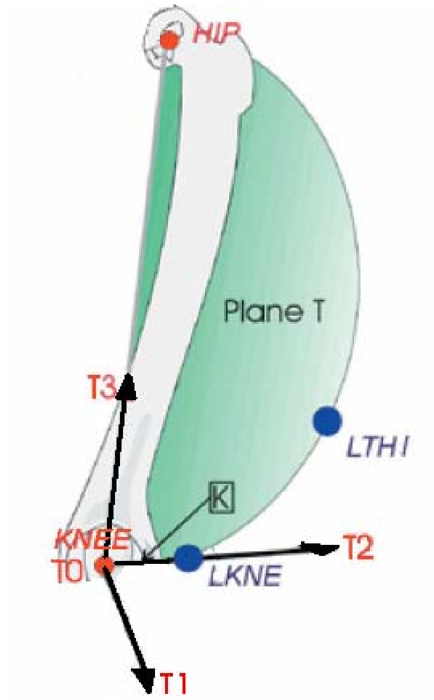


Figure 3.25
Kiss-GAIT – Thigh Coordinate System

Figure 3.26
VCM – Thigh Coordinate System

<u>VCM – Thigh Coordinate System</u>

T0 – The origin is located at estimated KJC.

T3 – The first axis joins the KJC and HJC and lies in the plane formed by the HJC and the markers THI and KNE.

T2 – The second axis also lies in the plane formed by the HJC and the markers THI and KNE and passes through marker KNE and the KJC, which lies at a distance equal to half knee width plus half marker diameter from KNE.

T1 – The third axis is perpendicular to the first and second.

Anatomical coordinate systems for right and left shank used in Kiss-GAIT and VCM are given in Figure 3.27 and 3.28.

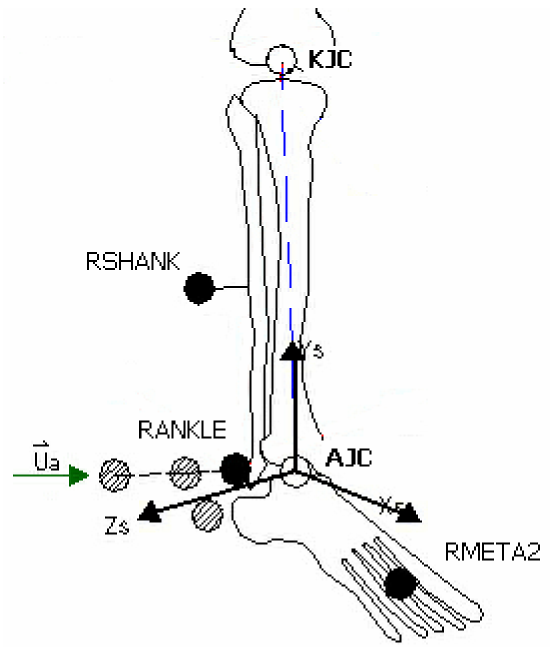


Figure 3.27
Kiss-GAIT – Shank Coordinate System

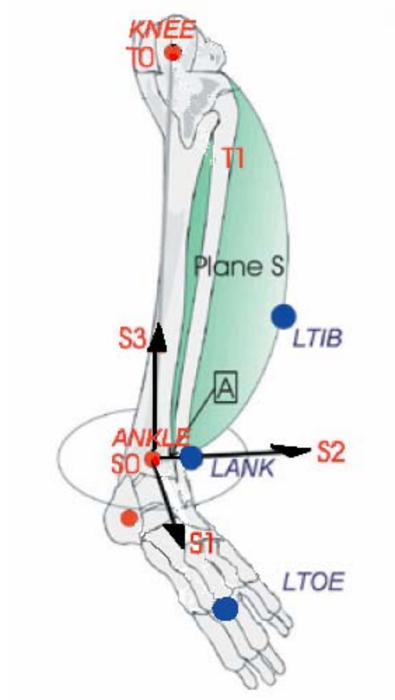


Figure 3.28
VCM – Shank Coordinate System

Kiss-GAIT – Shank Coordinate System

O_s – The origin is located at estimated AJC.

Y_s – The Y axis joins the origin with the KJC and its positive direction is proximal.

X_s – The X axis is orthogonal to the plane defined by KJC, AJC and $\vec{u}_a$ (ankle axis) and its positive direction is anterior.

Z_s – The Z axis is perpendicular to other two axes.

VCM – Shank Coordinate System

S0 – The origin is located at estimated ankle joint center.

S3 – The first axis joins the AJC and KJC and lies in the plane formed by the KJC and the markers TIB and ANK.

S2 – The second axis also lies in the plane formed by the KJC and the markers TIB and ANK and passes through marker ANK and the AJC, which lies at a distance equal to half ankle width plus half marker diameter from ANK.

S1 – The third axis is perpendicular to the first and second.

Marker placement of foot is shown in Figure 3.29 and 3.30. As seen in figures, the foot is defined by the single vector joining the ankle joint center to second metatarsal marker. The relative alignment of this vector with respect to the long axis of the foot is calculated from the static trial, using an additional calibration marker attached to the heel.

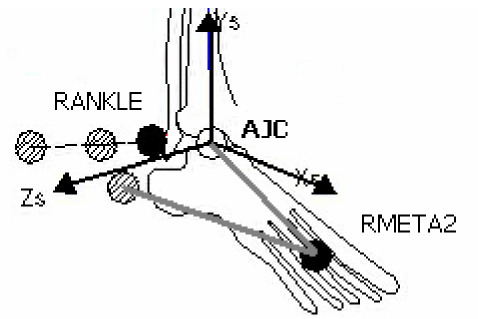


Figure 3.29
Kiss-GAIT – Marker placement of foot

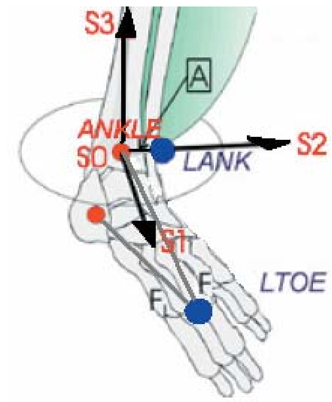


Figure 3.30
VCM – Marker placement of foot

Table 3.5 gives a summary of the anatomical coordinate system definitions used in Kiss-GAIT and VCM. First axis represents the medial-lateral axis where the flexion/extension takes place. Second axis is the posterior-anterior axis and the third axis is the proximal-distal axis.

Table 3.5 Axes of Anatomical Coordinate Systems

		Kiss-GAIT	VCM
PELVIS	**1**	Along LASIS-RASIS, towards RASIS	Along LASIS-RASIS, towards LASIS
	2	Perpendicular to other two axes	Lies in the plane defined by LASI, RASI, SACR, forming a right angle with the first axis
	3	Perpendicular to the plane defined by RASIS, LASIS, SACRUM, in superior direction	Perpendicular to other two axes
THIGH	**1**	Perpendicular to other two axes	Lies in the plane defined by HJC, THI and LKNE, and passes through LKNE and KJC
	2	Perpendicular to the plane defined by HJC, KJC and knee axis, in anterior direction	Perpendicular to other two axes
	3	Along KJC – HJC, towards HJC	Along KJC – HJC, towards HJC
SHANK	**1**	Perpendicular to other two axes	Lies in the plane defined by KJC, LTIB and ANK, and passes through ANK and AJC
	2	Perpendicular to the plane defined by KJC, AJC and ankle axis, in anterior direction	Perpendicular to other two axes
	3	Along AJC-KJC, towards KJC	Along AJC-KJC, towards KJC

3.3.6 Anatomical Joint Angle Definitions

Characterization of joint motion in terms of anatomical planes requires that motion be expressed in terms of orientation about three orthogonal axes. Both Kiss-GAIT and VCM use Euler (Cardan) angles to provide this 3D joint representation. This is a method of describing the orientation of one coordinate system relative to another.

According to Euler model, which involves a specific sequence of rotations, the neutral position (relative rotation angles between segments are zero) is defined when the local coordinate system on the distal segment coincides with the local coordinate system on the proximal segment. From this neutral position, the distal segment is assumed to move through three successive finite rotations to attain its new configuration.

The disadvantage of ordered Euler angles is their sequence dependency such that different sequences yield different numerical values of the angles for the same orientation.

The joint coordinate system was proposed as a standard convention by Grood and Suntay (1983) in order to eliminate the sequence dependency of Euler angles. JCS defines relative rotation of two bodies about two segment-fixed axes and a floating axis. Provided that the body-fixed axes are selected wisely, this convention yields either directly the anatomical angles or the resulting angles are easily convertible to the anatomical convention.

In both Kiss-GAIT and VCM, anatomical angles were defined based on the Grood and Suntay convention, which is demonstrated in the Figure 3.31.

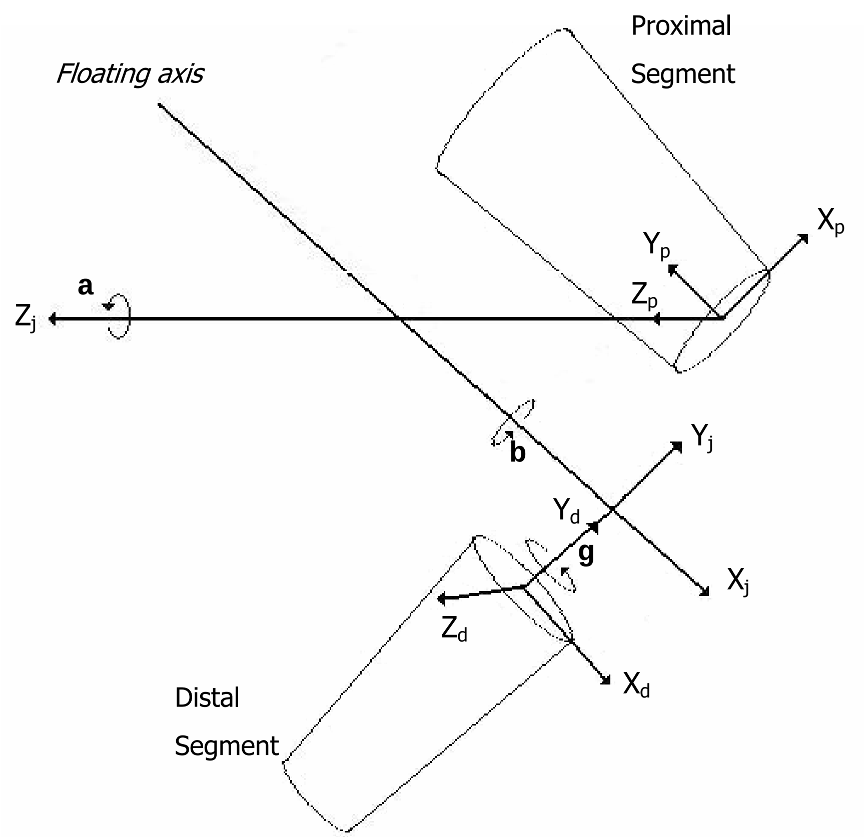


Figure 3.31 Joint Coordinate System proposed by Grood and Suntay

- **First rotation** (**a**): *Flexion and extension* about the medial-lateral axis of the proximal (or absolute) segment.

- **Third rotation** (**b**): *Internal and external rotations* about the longitudinal axis of the distal segment.

- **Second rotation** (**g**): *Abduction and adduction* about a floating axis (posterior-anterior axis) that is defined as being perpendicular to each of the two body fixed (flexion/extension and internal/external rotation) axes.

These angle definitions can be a little more easily understood by referring to Figures 3.32 and 3.33, which illustrate the left knee.

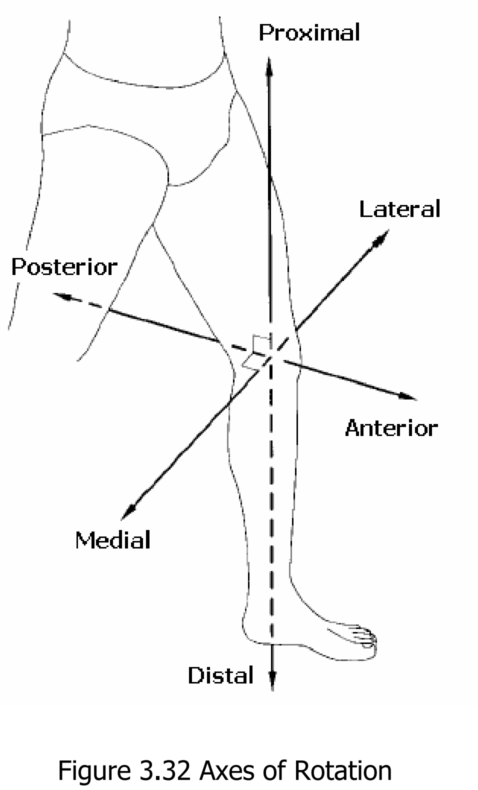


Figure 3.32 Axes of Rotation

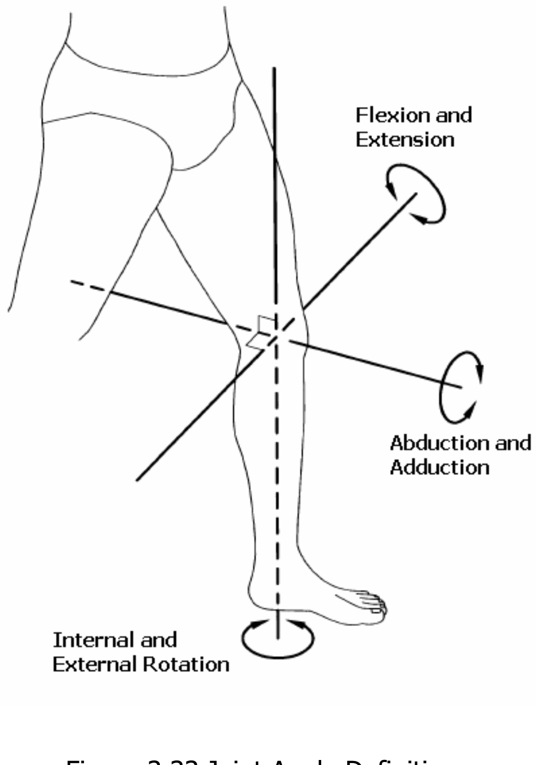


Figure 3.33 Joint Angle Definitions

(Adapted from *Dynamics of Human Gait*, by C. L. Vaughan, B. L. Davis, J. C. O'Connor, 1999, Cape Town: Kiboho Publishers)

Descriptions for each of the joint angles calculated by Kiss-GAIT and VCM are presented in Table 3.6.

Table 3.6 Descriptions of Joint Angles

Angle	Absolute/Relative	with respect to	Anatomical Plane
Pelvic Tilt	Absolute	Laboratory	Sagittal
Pelvic Obliquity	Absolute	Floating	Coronal
Pelvic Rotation	Absolute	Pelvis	Transverse
Hip Flexion	Relative	Pelvis	Sagittal
Hip Abduction	Relative	Floating	Coronal
Hip Rotation	Relative	Thigh	Transverse
Knee Flexion	Relative	Thigh	Sagittal
Knee Valgus	Relative	Floating	Coronal
Knee Rotation	Relative	Shank	Transverse
Ankle Dorsiflexion	Relative	Shank	Sagittal
Foot Rotation	Relative	n/a	n/a
Foot Alignment	Absolute	n/a	n/a

As can be seen from the table, knee rotation is a relative angle measured between the thigh as the proximal segment and the shank as the distal segment. Its goniometric axis is fixed to the shank as the distal segment.

Foot rotation and foot alignment, also known as foot progression, are not expressed in terms of goniometric axes, since the ankle angles are not calculated as strict Euler angles. Both rotations measure the alignment of the foot, the first relative to the shank, and the second as an absolute angle in the horizontal plane.

Absolute angles are measured relative to the laboratory axes with the forward and lateral axes selected according to the direction of walking.

3.4 FILE TYPES

KISS and VICON motion analysis systems produce and use several data file types in different stages of their own programs. All are explained briefly in the following sections.

3.4.1 KISS

File types used in data acquisition software Kiss-DAQ and data analysis software Kiss-GAIT are listed in Table 3.7, including file extensions and their descriptions.

Table 3.7 KISS File Types

	FILE EXTENSION	**FILE DESCRIPTIONS**
Kiss-DAQ	KUR	Data file that keeps the configuration of the current work in the program.
	CAL	Data file that stores calibration parameters.
	LIN	Data file that stores linearization parameters.
	HVD	Binary unprocessed data file that stores the data received from a single camera.
	EMG	Data file that stores the electromyography data received from data acquisition card.
	KUV	Data file that stores the force plate data received from data acquisition card.
Kiss-GAIT	MRK	Marker data file.
	GRF	Ground reaction force data file.
	EMG	EMG data file.
	YOR	**Binary file that are created whenever video data is reconstructed, labeled and saved.**
	BVD	Combination of four files for a specific trial, which are KUR, YOR, KUV and EMG .
	TMP	File including the calculated time distance parameters.
	STA	Static data file.
	ANG	Joint angle data file (raw).
	SAN	Smoothed angles file.
	MOM	Moment data file.
	POW	Power data file.
	VEL	Velocity data file.
	ACC	Acceleration data file.

3.4.2 VICON

The Vicon system generates many different file types, and most of these are managed automatically. Summary of Vicon file types are given in Table 3.8.

Table 3.8 VICON File Types

FILE EXTENSION	**FILE DESCRIPTIONS**
CAR	All parameters required for motion capture and reconstruction. In general these are changed using the system menu setup commands.
CFG	ASCII text file that holds a record of those parameters which normally remain constant throughout a session, such as the names of kinematic markers, EMG analog channel assignments, etc.
CRO	Coordinates of markers on calibration reference objects. Can contain information on several calibration objects.
CP	Calibration parameters for a set of cameras. Created during camera calibration and used when data from these cameras are processed.
LP	Linearization parameters for a set of cameras. Created during camera linearization and used when data from these cameras are processed.
MKR	Information about a specific marker set.
TVD	Binary unprocessed data file created when video data is captured. This is the data used for reconstruction – which in turn produces the C3D file. Also created during camera calibration.
VAD	Binary unprocessed data file created whenever analog data is captured.
MPG	Movie file format captured by digital camera, commonly known as MPEG.
C3D	**Binary file created whenever video data is reconstructed, labeled and saved. It contains 3D trajectory, force plate and EMG data, and it also contains marker identification labels, event labels and numerous other parameters.**
GCD	Gait cycle data file is the primary output data file of the Vicon Clinical Manager. It contains joint angles, moments and powers, EMG, and gait cycle parameters, and can be extended to contain many other types of gait variable.
RPT	ASCII text file that contains instructions used by VCM to format the content, layout and fonts of graphical clinical reports.

CHAPTER 4

KISS VERSUS VICON:

A PERFORMANCE COMPARISON

4.1 THE NEED

Automated gait analysis systems provide an objective tool for recording and evaluating human movement. Through gait analysis, kinematic data are acquired and analyzed to provide information that is ultimately interpreted by clinicians to make an assessment or used by researchers to develop new treatments and expand the knowledge available.

It is quite important that the validity of gait analysis systems be established in order to consider the data of value to clinicians or researchers. Measurement validity reflects the extent to which an instrument measures what is intended to measure.

As with any empirical process, quantitative gait analysis utilizes a well-defined protocol for data collection and reduction. Both data collection and reduction stages of gait analysis are prone to many potential sources of error.

As Cappozzo (1991) pointed out that assessment of variables in joint kinematics is affected by two types of inaccuracies. One is associated with the error with which the three-dimensional coordinates of a marker are reconstructed (instrumental error). The other is the error with which a bony landmark location in space is determined (skin movement artifacts).

This chapter focuses on the error which affects the reconstruction of marker trajectories, namely the instrumental error. These errors can be divided into two classes: random errors and systematic errors.

Random error is caused by the quantization inherent in the digitizing process which transforms the marker image coordinates into numerical values. Systematic errors can be introduced by many factors that affect the accuracy and resolution of camera based motion analysis systems. According to Holden, Selbie and Stanhope (2003), errors introduced by the motion capture components can be caused by uncorrected camera non-linearities, poor three-dimensional external camera calibration and/or target image distortions. Furthermore, marker size, parameters of the CCD image sensor, and the image processing algorithms may influence the data accuracy as well. Additional systematic errors may also be present due to laboratory layout or design such as camera arrangement and excessive ambient noise.

These challenges are compounded when comparing results from any two laboratories where different hardware and software are employed as well as different data collection and reduction protocols and staff training or experience.

This chapter is devoted to compare the data acquisition performance of the two gait analysis systems namely, KISS and VICON. Both systems were evaluated before individually through system specific tests.

The performance of the measurement instrumentation and the data acquisition software of the KISS system were thoroughly evaluated by Karpat (2000). Karpat determined the accuracy and resolution of the kinematic data acquisition system through a set of static and dynamic tests in which a stick with markers attached to the ends was used.

The technical performance of the VICON 370 system was evaluated in a number of different studies in the literature. Dorociak and Cuddeford (1995), Engler et al. (1996) and Bhimji et al. (2000) assessed the accuracy of Vicon 370 system employed in different laboratories through specific tests.

Engler et al. (1996) used a fixture consisting four reflective targets rotating about a fixed axis for the assessment of the accuracy of the 6-camera, 120 Hz Vicon 370 movement analysis system. Bhimji et al. (2000) performed static and dynamic experiments included the measurement of small, medium and large distances between two markers, and they conducted a ball drop test and a rotating clock arm test for determining the dynamic accuracy.

Static accuracy of Ankara University Clinical Gait Analysis Laboratory equipped with five-camera Vicon 370 system was evaluated through a few studies which were unpublished.

This study was intended to measure the accuracy of these two systems based on the same test protocol which is described in details in the following section.

4.2 TEST PROTOCOL

4.2.1 Methodology

Accuracy of a motion capture system can be divided into static and dynamic accuracy. Static accuracy determines how accurately the system can yield the location of a static object, whereas dynamic accuracy reflects how well any changes in the position or orientation of a moving object are measured.

Static and dynamic accuracies must be considered separately, since they are not the same because of the camera synchronization error. The cameras update images at a certain frame rate, and the position of a moving object can not be known between measurement updates.

When testing 3D camera systems, it is difficult to measure and test the positions of the markers with a great accuracy with respect to the coordinate system in the measurement space. A widely used solution is to determine the accuracy of the distance between two markers placed on the points having known distance, which can be referred as the relative accuracy. Another approach is to move a marker along a well-defined trajectory, and then the deviation from the known trajectory is characterized as the accuracy.

As already mentioned in Section 4.1, Karpat (2000) and Bhimji et al. (2000) evaluated the static and dynamic accuracy of KISS and VICON systems, respectively. They both concluded that the dynamic accuracy is often a lot worse than the static accuracy for an optical position sensing system.

Due to their findings and considering some initial tests performed in both laboratories, it has been found to be sufficient to present results based only on dynamic accuracy tests in this study.

Since the aim of this study is to compare two gait analysis systems, testing and comparing the dynamic accuracy requires a testing device having a standard motion. The predictable nature of a pendulum swing and its comparability to the motion of body parts during gait was felt to be a suitable motion. Therefore, a physical pendulum was used to test the accuracy of the KISS and VICON motion analysis systems.

4.2.2 Simple Gravity Pendulum: Theory

A simple gravity pendulum consists of a weight on the end of a rigid rod (or an inextensible string), which, when released from rest at an angle, will swing back and forth under the influence of gravity over its central (lowest) point (Figure 4.1).

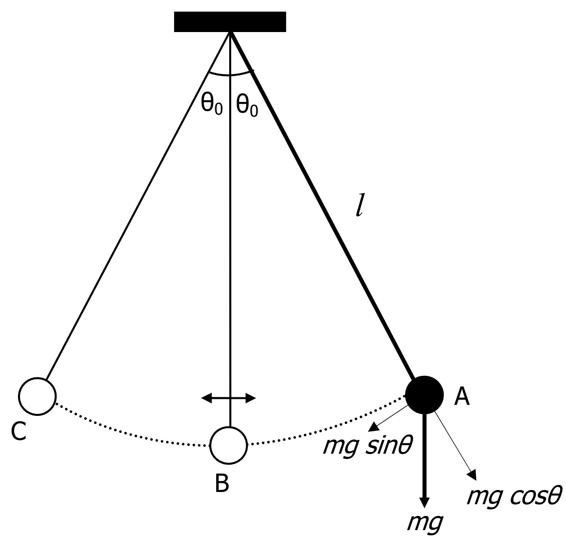


Figure 4.1 Simple Gravity Pendulum

By applying Newton's Second Law of Motion for rotational motions, the equation of motion for the pendulum can be obtained:

$$\tau = I \cdot \alpha \;\Rightarrow\; -mg\sin\theta \cdot l = ml^2 \frac{d^2\theta}{dt^2} \tag{4.1}$$

where:

m = mass of the pendulum bob

l = length of pendulum

g = gravitational acceleration

θ = angular position of the bob

$\frac{d^2\theta}{dt^2} = \alpha$, angular acceleration of the bob

Rearranging the Equation 4.1,

$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\sin\theta = 0 \tag{4.2}$$

If the amplitude of angular displacement is small enough that the small angle approximation ($\sin\theta \approx \theta$ if and only if $|\theta| << 1$ rad) holds true, then the equation of motion reduces to the equation of simple harmonic motion.

$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\theta = 0 \tag{4.3}$$

The motion described in Figure 4.2 is the simple harmonic motion. At time t=0 that corresponds to the instant when the mass is first released, the mass is located at A, which makes an angle θ_0 with the vertical. The mass swings, passes through B where $\theta=0$, and reaches C where $\theta=\theta_0$, in the absence of friction. At C, the mass momentarily stops and then reverses its direction of motion from clockwise to counterclockwise. It passes through B again and returns to A, thus completing one full cycle in a time interval of T seconds, which is called the period of harmonic motion.

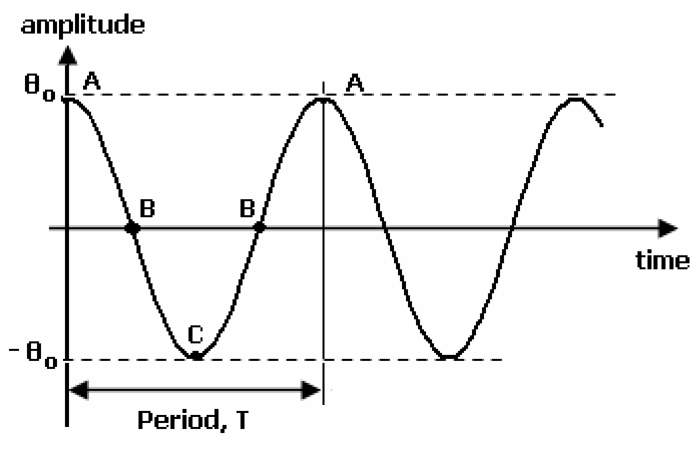


Figure 4.2 Undamped Simple Harmonic Motion

The solution to the Equation 4.3 is the oscillatory function

$$\theta(t) = \theta_0 \cos\left(\sqrt{\frac{g}{l}}t\right) \qquad |\theta_0| << 1 \text{ rad} \tag{4.4}$$

where:

θ_0 = initial angle between the string and the vertical

$\sqrt{\frac{g}{l}}$ = ω, angular frequency of the motion

Angular frequency is measured in radians per second. Simple harmonic motion can be considered to be the projection of uniform circular motion. Then, one revolution is equal to 2π radians, and hence

$$\omega = \sqrt{\frac{g}{l}} = \frac{2\pi}{T_0} \tag{4.5}$$

where T_0 is the period of a complete oscillation. Then, the period of pendulum motion can be easily found by the Equation 4.6 for small angles.

$$T = 2\pi\sqrt{\frac{l}{g}} \qquad |\theta_0| << 1 \text{ rad} \tag{4.6}$$

4.2.3 Experimental Set-Up

Plumb bob of the surveyor's telescope in the Biomechanics Laboratory was used as pendulum in the experiments. Steel plumb bob (mass 0.2 kg) attached to a string of almost 1.2 m was suspended from the hook of a bird cage hanging stand and released to swing back and forth (Figure 4.3).

Figure 4.3 Pendulum assembly used to test the accuracy of the systems

0.5 inch (approx. 15 mm) diameter marker balls made from wood were covered with retroreflective material and affixed to three locations on the string of the pendulum. One of the markers was fixed just below the hook, second was fixed at the end of the string and the last marker was fixed in the middle of the string.

4.3 DATA COLLECTION

Cameras were calibrated according to the procedures explained in Section 3.2.1 before conducting the experiments. Calibration parameters were found within the acceptable range.

Pendulum assembly was located roughly at the center of the calibration volume. Pendulum bob was pulled aside from the vertical with some angle, and then gently released, so that the pendulum swings back and forth within a vertical plane.

The distance covered by the bob with each oscillation gradually shortened over time due to internal friction and air resistance. When the amplitude of oscillations was small enough that the small angle approximation is valid, data capture was started. Data was collected for 12 seconds in each trial, which corresponds to 300 frames of data at a frame capture rate of 25 Hz. This frame rate can be considered fairly low for motion tracking, but it is sufficient for testing purposes.

After several trials were recorded at the center of the calibration volume of VICON system, the whole assembly was located in different places within the volume with a few data captures being taken in each position in order to evaluate the accuracy of the system in different regions of the laboratory.

KISS system had already been elaborately evaluated by Karpat (2000) in terms of static and dynamic accuracy for different locations in calibration volume; therefore pendulum test trials were only performed at the center of the calibration volume of KISS system.

4.4 DATA PROCESSING

All test series were consecutively processed by the data acquisition software of the systems and the 3D marker trajectories were reconstructed (Figure 4.4). Three markers attached on the string were first labeled as pivot, midpoint and endpoint. Then the 3D coordinates were checked for dropped-out markers and if there were any, they were connected linearly. Finally, the best record was selected for the accuracy analysis.

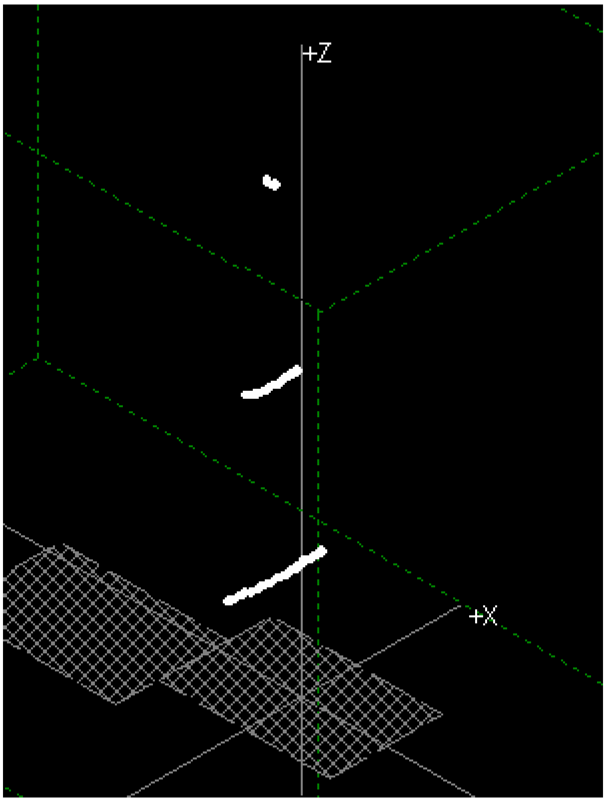


Figure 4.4 3D marker trajectories reconstructed by Kiss-DAQ (for one full cycle)

4.5 DATA ANALYSIS

3D reconstructed data sets pertaining to three markers on the string were extracted from the data acquisition software of the systems and imported to Microsoft Excel®. One complete cycle data (from the right extreme, over to the left extreme and back again) including 57 data points were examined in terms of several parameters of measurement interest. These included period estimation, length estimation and accuracy of linear estimates.

4.6 RESULTS AND DISCUSSION

4.6.1 Period Estimation

The predicted value of the pendulum period was calculated from small angle approximation using the Equation 4.6.

$$T_{predicted} = 2\pi\sqrt{\frac{1.20\,m}{9.81\,m/s^2}} = 2.20 \text{ s} \qquad |\theta_0| << 1 \text{ rad} \qquad (4.7)$$

In order to verify the validity of the Equation 4.7, largest angle attained by the pendulum in the cycle must be determined.

In the analysis of the experiments, first frame was selected to coincide with the instant at which the bob reached the highest point where the speed was zero. The instant where the bob passed through the lowest point of the trajectory, i.e. direction of the string coincided with the vertical axis was also indicated. The angle between these two positions of the string corresponding to mentioned time instants will give the largest angle attained by the pendulum (Figure 4.5).

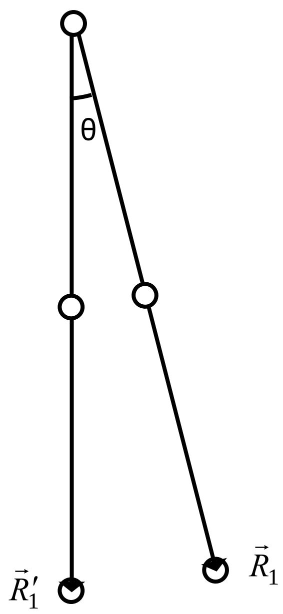


Figure 4.5 Largest angle attained by the pendulum

If a vector is defined from the pendulum pivot point to the end point as shown in Figure 4.5, the dot product of successive pair of the vectors $\vec{R}_1$ and $\vec{R}_1'$ can be used to find the pendulum angle.

$$\vec{R}_1 \cdot \vec{R}_1' = |\vec{R}_1| \cdot |\vec{R}_1'| \cdot \cos\theta \qquad (4.8)$$

For KISS experiment:

1st frame: $\vec{R}_1 = 159.27\vec{i} - 5.94\vec{j} - 1186.48\vec{k}$ (highest point) (4.9)

15th frame: $\vec{R}_1' = -1.39\vec{i} - 24.22\vec{j} - 1195.33\vec{k}$ (lowest point) (4.10)

For VICON experiment:

1st frame: $\vec{R}_1 = -10.306\vec{i} + 181.535\vec{j} - 1206.37\vec{k}$ (highest point) (4.11)

15th frame: $\vec{R}_1' = -2.061\vec{i} - 7.293\vec{j} - 1221.12\vec{k}$ (lowest point) (4.12)

Inserting the corresponding values into the Equation 4.8 yields θ:

For KISS:

$\cos\theta = 0.99084 \Rightarrow \theta = 0.13546$ rad $<<$ 1 rad ✓

(Small angle approximation is valid)

For VICON:

$\cos\theta = 0.98794 \Rightarrow \theta = 0.15548$ rad $<<$ 1 rad ✓

(Small angle approximation is valid)

Therefore, period of oscillation determined from the positional data obtained by the cameras can be compared to the predicted period of oscillation calculated by the Equation 4.7.

In the experiments performed in both systems, pendulum completes its full cycle between the frames 0 to 56. Having considered the sampling frequency of 25 Hz, measured value of pendulum period can be found.

$$T_{measured} = \frac{56}{25} = 2.24 \text{ s} \tag{4.13}$$

Absolute error in magnitude was simply calculated as the absolute value of the difference between the measured and predicted values as in the Equation 4.14.

$$Abs(Err) = \left|T_{measured} - T_{predicted}\right| \tag{4.14}$$
$$= \left|2.24 - 2.20\right|$$
$$= 0.04 \text{ s}$$

Absolute error of about 0.04 s corresponds to the percent relative error;

$$\%(Err) = \frac{Abs(Err)}{Predicted\ Value} \times 100\% \tag{4.15}$$
$$= \frac{0.04}{2.20} \times 100\%$$
$$= 1.82\%$$

This 1.82 percent relative error may be explained by the approximations for gravitational acceleration and Pi values, as well as error in measuring the length of the pendulum. Moreover, a major contributor in the dynamic accuracy is the update rate of the cameras, which was 25 FPS in this experiment. It can be concluded that both systems demonstrate good accuracy when measuring the timing of a moving body under predictable conditions.

4.6.2 Length Estimation

4.6.2.1 Near the Center of the Calibration Volume

True values of the distances were measured by a tape measure, when the pendulum was hanging at rest. The distance between the markers labeled by pivot and endpoint was 120 cm, and the distance between the markers labeled by pivot and midpoint was 60 cm before the experiment, which is conducted in KISS system.

Unfortunately, some changes were observed in the distances between markers after the experiment had been performed in VICON system. Most probably, markers have been slightly displaced on the string between two dates that the experiments held on. And also, a small elongation may have been occurred in the length of the string. After the second experiment conducted in VICON system, pivot-to-endpoint distance was measured as 122 cm, and pivot-to-midpoint distance was measured as 62 cm.

This unfortunate difference will of course be seen in the measurements made by KISS and VICON systems. Therefore, the accuracies of the systems are required to be calculated separately rather than directly comparing the measurement results.

First, two different distances of interest are selected for determining the accuracy of the distance measurements obtained by the optical motion capture systems. For this purpose, two vectors were defined associated with two different distances of interest.

One vector was defined from pivot to end-point ($\vec{R}_1 = \vec{P}_3 - \vec{P}_1$), another vector was defined from pivot to mid-point ($\vec{R}_2 = \vec{P}_2 - \vec{P}_1$) which can be seen from the schematic representation given in Figure 4.6.

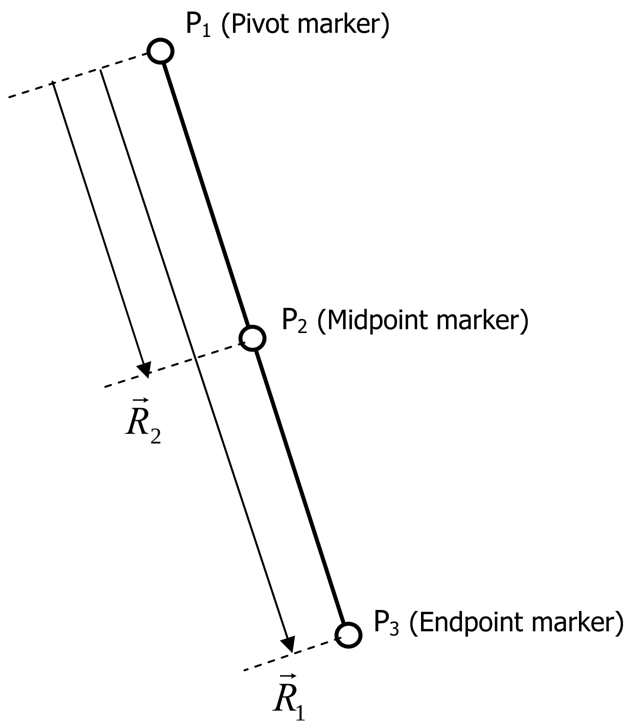


Figure 4.6 Relative distances between markers

Magnitudes of the vectors $\vec{R}_1$ and $\vec{R}_2$ were calculated from marker coordinates data reconstructed by KISS and VICON systems. Change in measured distances during one complete cycle of pendulum motion corresponding to 57 frames is plotted in Figures 4.7 and 4.8.

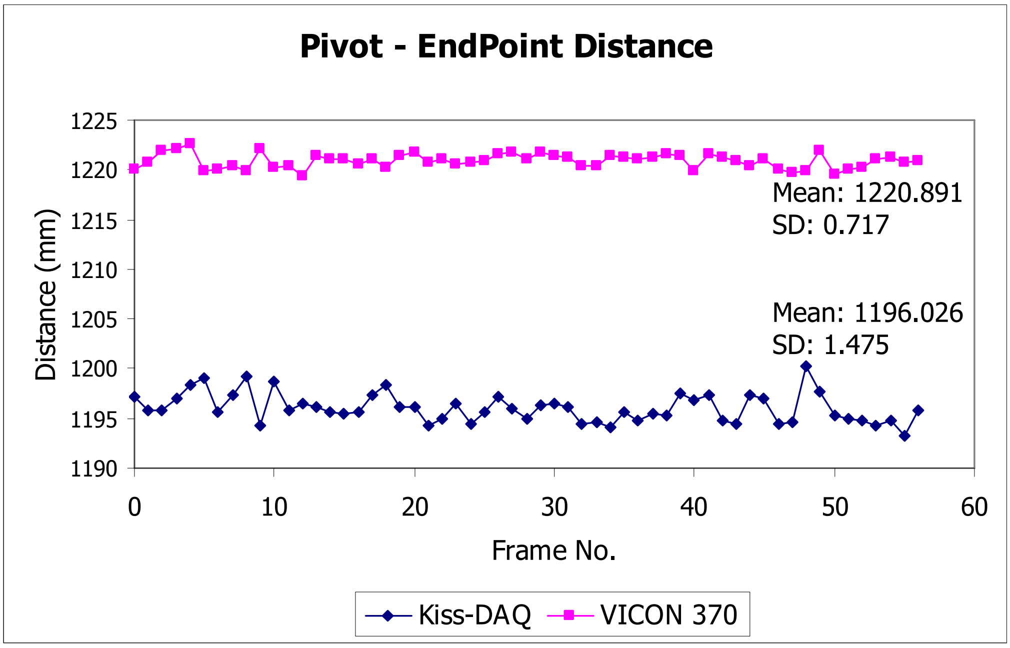


Figure 4.7 Measured distance from pivot marker to end-point marker

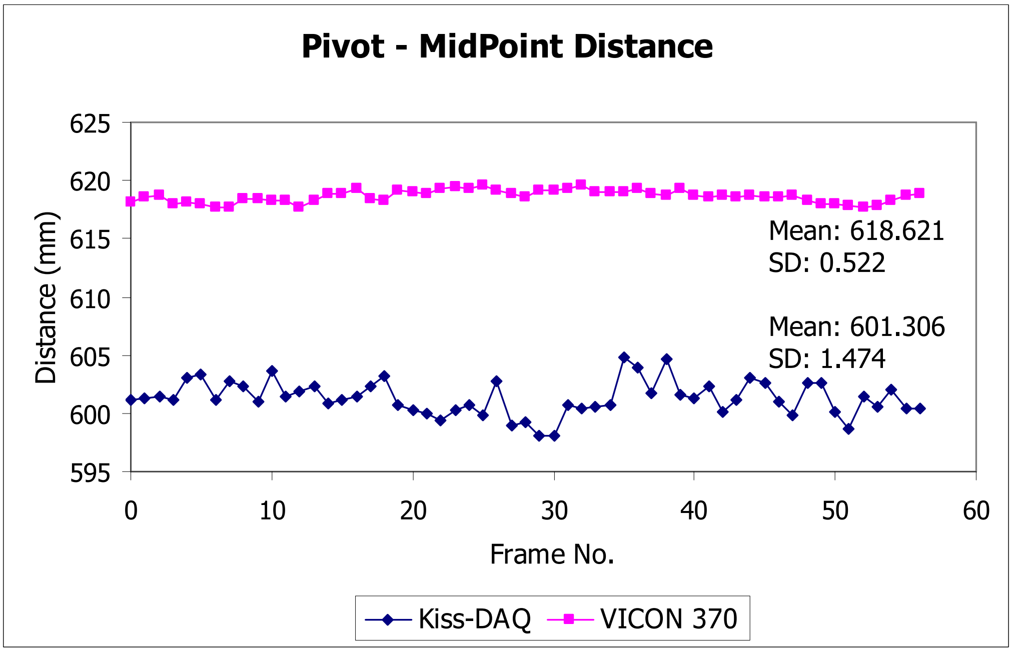


Figure 4.8 Measured distance from pivot marker to mid-point marker

Calculated distance between moving markers was averaged over 57 frames, which corresponds to one complete cycle of the pendulum. The average error magnitude and the standard deviation (SD) of measurements obtained by KISS and VICON systems are presented in Table 4.1.

Table 4.1 Mean and Standard Deviation (in mm) of Reconstructed Length Calculated by KISS and VICON Systems for Reference Lengths

	Reference Length	Mean (n=57)	Standard Deviation	Mean Absolute Error
VICON	1220	1220.891	0.717	0.891
KISS	1200	1196.026	1.475	3.974
VICON	620	618.621	0.522	1.379
KISS	600	601.306	1.474	1.306

Unintentional change in the experimental set-up that is the change in relative distance between markers is clearly seen on Table 4.1. Therefore, it is meaningless to compare the mean of the measurements taken by two systems during pendulum's motion. However, distance measured by tape measure can be a good reference for accuracy evaluation.

By taking tape measures as reference length, mean absolute errors (|Reference Length – Mean Measured Length|) are calculated and presented in Table 4.1. As seen from the table, mean absolute error was analyzed at a level ranging from 0.891 mm to 3.974 mm. Inaccuracy of the reference instrument (tape measure) also contributes to this error, since it was too difficult to measure the exact distance between the physical center of the markers on the suspended string.

The standard deviations of the reconstructed length for two different reference lengths were obtained to estimate the amount of variation (noise) in the data (Table 4.1). Since the standard deviation values of VICON are lower than those of KISS, it can be concluded VICON gives more precise measurements than KISS. Variations in KISS system are considered to be caused mainly by random noise and calibration imperfections. Or else, this problem may happen due to a combination of CCD quality and usage conditions or age deterioration of the cameras.

VICON system has slightly higher variability at the long distance, then it can be concluded that VICON is more precise in measuring targets at close relative distance.

In assessment of the gait analysis systems, accuracy of the system is commonly calculated by using the formula (Equation 4.16) proposed by Hall (1990) (as cited in Abuzzahab et al., 1996).

$$A = \left(1 - \frac{\left| X_w - \frac{1}{n} \cdot \sum_{i=0}^{n-1} d_i \right|}{\frac{1}{n} \cdot \sum_{i=0}^{n-1} d_i} \right) \times 100\% \tag{4.16}$$

where:

A = system accuracy as a percentage

X_w = worst data point; data point having maximum absolute error

n = total number of samples

d_i = reconstructed length

According to Equation 4.16, accuracy of the KISS and VICON systems were calculated and presented in Table 4.2.

Table 4.2 Comparison of Accuracy of KISS and VICON Systems

	Reference Length (mm)	Accuracy (%)
KISS	1200	99.769
VICON	1220	99.864
KISS	600	99.426
VICON	620	99.844

Table 4.2 shows that accuracy of distance measurements obtained with KISS and VICON systems are remarkably high, and overall accuracies of measurements closer to the center of the data acquisition field were found to be clinically acceptable (mean length error < 4 mm even in the worst case) for all tests.

Although accuracy of VICON system is slightly higher than that of KISS, there is no significant difference between accuracies of the two systems.

4.6.2.2 Near to the Extremities of the Calibration Volume

Analyses till now were about pendulum motion trial which was recorded at the center of the calibration volumes of KISS and VICON systems. In order to evaluate the accuracy of different locations within the laboratory, a few more data captures were taken in VICON system. Two more trials were captured, when pendulum assembly was located at two ends of the walking platform. Figure 4.9 illustrates three different locations marked by A, B and C, where pendulum tests were conducted.

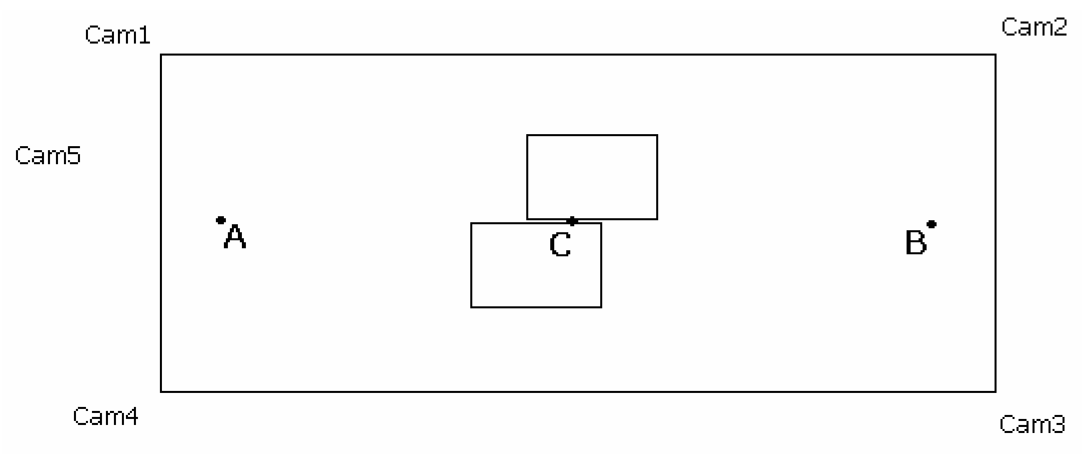


Figure 4.9 Locations of pendulum assembly on the walking platform (top view)

Reference lengths were calculated for each of the three locations in Figure 4.10 and 4.11. Mean, standard deviation and accuracy of measurements obtained in different locations within the calibration volume of VICON system are presented in Table 4.3.

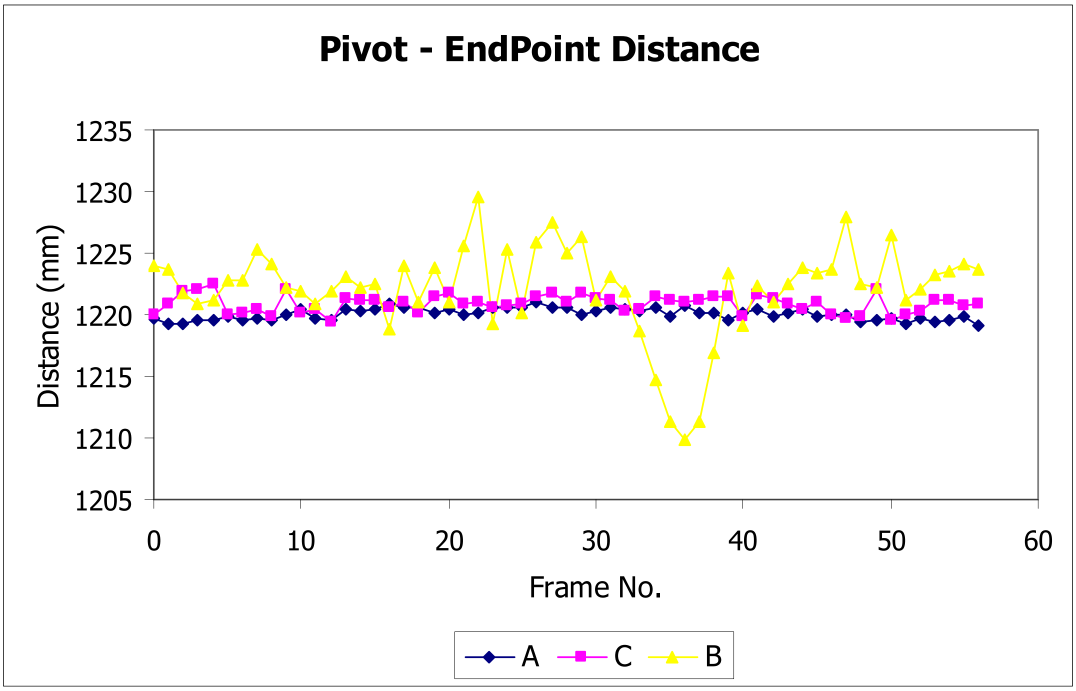


Figure 4.10 Pivot-to Endpoint distance for each location within the calibration volume

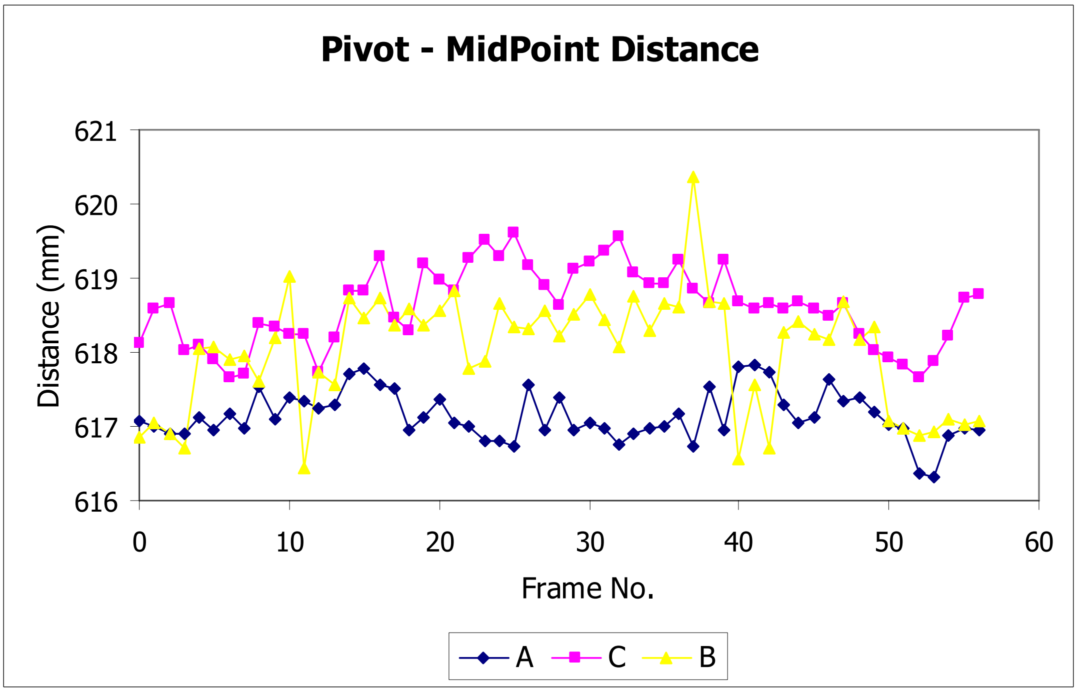


Figure 4.11 Pivot-to Midpoint distance for each location within the calibration volume

Table 4.3 Mean, Standard Deviation (in mm) and Accuracy of Reconstructed Length Calculated by VICON System at Three Different Locations

Location	1220 mm Reference Length			620 mm Reference Length		
	Mean (n=57)	Standard Deviation	Accuracy (%)	Mean (n=57)	Standard Deviation	Accuracy (%)
A	1220.052	0.465	99.918	617.144	0.329	99.866
B	1221.100	3.696	98.996	618.008	0.777	99.745
C	1220.891	0.717	99.864	618.621	0.522	99.844

Table 4.3 shows that VICON system gives the most accurate and precise results in location A, which is close to the region that three cameras are located. Accuracy and precision of the measurements decrease when approaching to the other side of the laboratory where there are only two cameras. This change may happen due to number of cameras, their placement and difference in each camera performance.

For locations A and C, system was considered to be consistent in calculating distances from reflective markers under dynamic conditions. However, their results for 620 mm length estimation differ from each other, whereas they give very consistent results for 1220 mm length estimation.

Measurements recorded at location B are considerably worse than the others. As can be seen on the Figure 4.10, there exist important outliers between frames 31 and 37. That is due to the unwanted absence of reconstructed markers in the endpoint marker trajectory. If a marker is occluded from the camera's view during motion capture, some coordinate data associated with that marker are missed and a gap can occur. In such a case, gaps can be filled solely linearly by the software of the systems which is responsible for 3D reconstruction.

It is evident that endpoint marker followed a circular arc trajectory during that period of time. Therefore, the difference between circular arc and linear trajectories is reflected in the graph.

As previously mentioned, Karpat (2000) performed dynamic accuracy tests in which a stick with markers at ends was moved inside the calibration volume of KISS system. This study concluded that the accuracy of KISS system decreases as going from window side to the door side of the laboratory. Therefore, it is recommended that gait trials should be initiated from the window side and early steps should be chosen for kinematic analysis.

A similar recommendation would be made for VICON system that gait trials should be started from the location A (side which is closer to three cameras) in Figure 4.9 and initial steps should be analyzed.

4.6.3 Collinearity Estimation

It is known that, three markers attached on the same string suspended from a point are collinear in actuality. In order to verify this collinearity condition, angle between the vectors $\vec{R}_1$ and $\vec{R}_2$ was calculated using the Equation 4.8 and plotted in Figure 4.12.

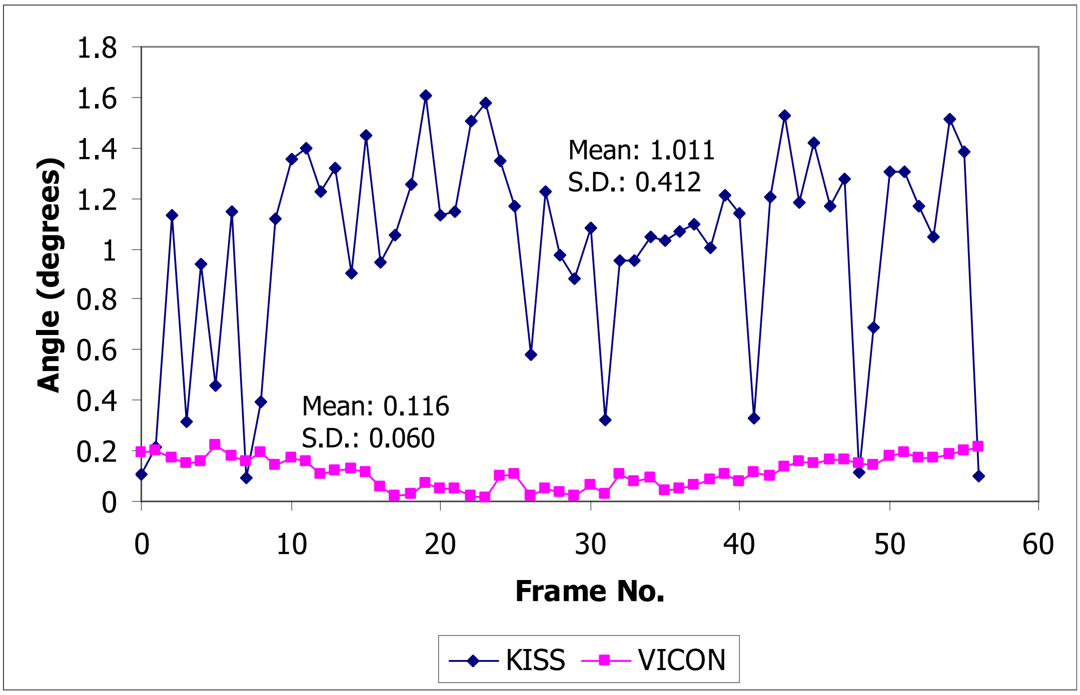


Figure 4.12 Angle between vectors $\vec{R}_1$ and $\vec{R}_2$

According to Figure 4.12, KISS system has much higher variation than VICON. In estimations obtained by KISS system, vectors $\vec{R}_1$ and $\vec{R}_2$ are away from being collinear. Such a change in the shape of an image results from imperfections or aberrations present in the optical system. This problem most probably results from distortion errors in the camera lens.

3D reconstruction algorithms require undistorted images in order to match corresponding points in successive frames and estimate the movement of objects in space. Dynamic calibration methods provide information about lens distortion, as well as position and orientation of cameras with respect to each other. Therefore, dynamic calibration is an essential step and plays a considerable role in minimizing the error in the resulting data due to instrument deficiency. High variation of KISS system can be reduced by a proper dynamic calibration.

CHAPTER 5

KISS VERSUS VICON:

COMPARISON OF KINEMATIC RESULTS

5.1 THE NEED

KISS and VICON gait analysis systems differ from each other in both data acquisition system and model-based gait analysis methodology which was previously discussed comprehensively in Chapter 3.

Consequently, these systems lead to different results in different stages of their own programs. Initially data acquisition performance of the systems was compared through the evaluation of marker image reconstruction accuracy and reported in Chapter 4.

However, performance evaluation alone is not sufficient to compare the performance of these gait analysis systems as a whole. Because gait models utilized by KISS and VICON use different calculations to determine joint center locations, segment orientations and three dimensional joint angles.

In this chapter, kinematic results of the KISS system were compared with those of the Ankara University based commercial VICON (Oxford Metrics Ltd., Oxford, UK) system, in view of evaluating the gait analysis methodology.

5.2 METHODOLOGY

The methodological approach implemented in this study for the purpose of kinematic results comparison between two systems has two main bases, and was clarified in the following. Summary of the experiments performed were illustrated in Figure 5.1.

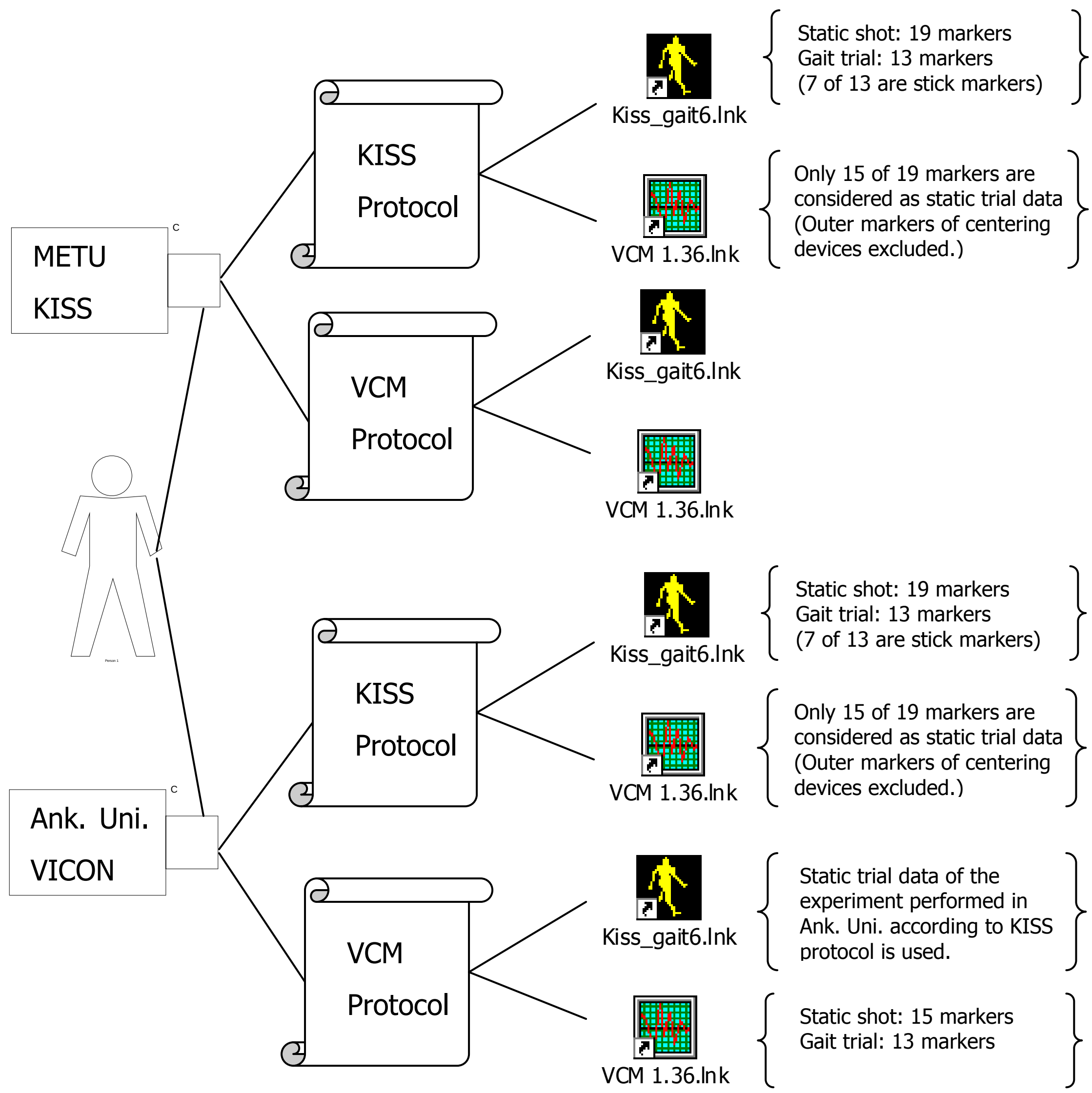


Figure 5.1 Summary of the experiments performed

Gait analyses were performed on an able-bodied volunteer (male, 27 years old, 83 kg, and 1.83 m) who currently had no known musculoskeletal injury or disease and was free of pain. Subject was experimented with KISS system in METU-Biomechanics Laboratory in two different sessions, one of which was according to KISS data collection protocol and the other one was according to VCM data collection protocol. Furthermore, for the same subject, gait experiments were conducted in VICON system of Ankara University by applying the same procedure.

Experiments were conducted in the morning and afternoon within the same day. Experiments began with the calibration of the optical motion capture system. Then, reflective markers were attached as described in Kiss-GAIT/VCM data collection protocol using double-sided adhesive tape. Marker locations were noted with a permanent marker to assess the repeatability of the test subject inter sessions. Anthropometric measurements such as leg lengths and knee and ankle widths were obtained as outlined in the Kiss-GAIT/VCM data collection protocol.

A static trial was performed prior to gait trials to provide a reference point for markers. One second of data was collected with subject standing in a stationary natural upright posture. Centering devices were removed, and surface markers were placed instead. The subject was first given some practice trial to familiarize himself with the experimental setting, and to determine the neutral pace. It is required that at least two complete steps fall within the calibration volume. During each session, the subject was instructed to walk at a self-selected comfortable speed along the walkway, looking forward in the plane of progression. Observed speeds were around 1.1 m/s in all sessions. In addition to the static trial, a minimum of five gait trials were captured.

After the walking trial had concluded, 3D motion data regarding the trial reconstructed by data acquisition software of the system on which the experiment was conducted. The trial with adequate data that have minimal marker loss during the strides of interest was selected as best record for further processing. Then 3D reconstructed data was given as an input into gait analysis software packages Kiss-GAIT and VCM separately, and the kinematic analyses were performed in both systems using the same kinematic data.

By analyzing the identical motion data captured with either hardware on two systems, direct comparison could be made between the software responsible for calculating joint kinematics. Furthermore, experiments performed in two systems with two different protocols enable to compare different data collection protocols.

Since both KISS and VICON stores its data in a different file format, they cannot interchange data freely. Therefore, the data from each system must be converted to be read by the other system's programs.

5.2.1 File Conversion

As previously mentioned VICON employs a widely used common format for storage of motion data – so called "C3D file format" whose file specification was published, and freely accessible (c3dformat.pdf, 2006). On the other hand, KISS has its own unique digital file format named YOR, which is abbreviated from *"yörünge"* which means trajectory in Turkish.

C3D and YOR file formats are binary file formats, and can be thought as identical files utilized by two different software platforms. Both contain 3D marker trajectories and marker identification labels.

Once an experiment was performed on either system, gait analysis was carried out directly in the corresponding gait analysis package of the system as usual. On the other hand, it is required to convert the 3D trajectory file to the format that can be read by the other system's platform.

For instance, if the system on which experiment was conducted is KISS, it is required to convert the YOR file to C3D file in order to be read the identical motion data by VICON system. In the opposite case, C3D file must be converted to YOR file.

File conversion procedures between KISS and VICON have been achieved by user-written programs and various C3D software applications available in the market that give the opportunities of viewing, editing and creating gait trial data.

5.2.1.1 YOR to C3D Conversion

In order to convert the YOR file to C3D, firstly YOR file is opened by a code named Plotter, user-interface that displays the content of YOR file and allows user to save YOR file as TXT format. After saving YOR as TXT, another program, C3D Editor (Motion Lab Systems, Inc., Baton Rouge, LA, USA), evaluation version can be obtained from C3D format web site www.c3d.org is used to import 3D trajectory data extracted from YOR file, into an available C3D file.

Although KISS and VICON use different global coordinate systems, there is no need to transform marker coordinates extracted from KISS system according to VICON. Because, VCM first determines the progression direction of the subject considering the pelvic markers position, and then makes the gait cycles ready to user for identifying gait events.

5.2.1.2 C3D to YOR Conversion

If converting the C3D file to YOR is the case, this time another software package, either C3D Exporter (Oxford Metrics Ltd., Oxford, UK) or RData2 ASCII Export (Motion Lab Systems, Inc., Baton Rouge, LA, USA) come into use. Utilizing these programs, C3D file is saved as TXT.

At this stage, transformation of the 3D coordinate data relative to the KISS global frame is required; since Kiss-GAIT starts the analysis with an assumption of that walking path coincides with the Y direction of the global coordinate system.

Global coordinate systems used by KISS and VICON systems were illustrated in Figure 3.12 and 3.13. According to those, 3D coordinate data exported from VICON system have to be rearranged relative to the KISS laboratory fixed coordinate frame using the transformation matrix constructed in the following.

$$\bar{r}^{(k)} = \hat{C}^{(k,v)} \cdot \bar{r}^{(v)} \tag{5.1}$$

where:

$\hat{C}^{(k,v)}$ = transformation matrix from F_v to F_k

$\vec{r}^{(k)}$ = column matrix representation of vector $\vec{r}$ in F_k

$\vec{r}^{(v)}$ = column matrix representation of vector $\vec{r}$ in F_v

F_v = global coordinate frame used in VICON 370 (Figure 3.13)

F_k = global coordinate frame used Kiss-DAQ (Figure 3.12)

According to Figure 3.12 and 3.13, rotation about Z – axis of F_v, gives the transformation matrix.

$$\hat{C}^{(k,v)} = \begin{bmatrix} \cos(-\pi/2) & -\sin(-\pi/2) & 0 \\ \sin(-\pi/2) & \cos(-\pi/2) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5.2}$$

If vector $\bar{r}^{(v)}$ is represented by $\begin{bmatrix} x \\ y \\ z \end{bmatrix}$, then inserting the known relations into the Equation 5.1 yields

$$\bar{r}^{(k)} = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} y \\ -x \\ z \end{bmatrix} \tag{5.3}$$

After the transformation is completed, a user-written java program is used in order to read TXT file and produce YOR as an output. The code written in Java™ is presented in Appendix A.

Once the file conversion tools between KISS and VICON have been available, these gait analysis systems gained the ability to read and analyze each other's motion data.

5.3 RESULTS AND DISCUSSION

Total of 20 trials of data were collected in 4 different sessions for the same subject. All trials were consecutively processed by the data acquisition software of the systems and the 3D marker trajectories were reconstructed. Markers attached on the lower extremity were first labeled according to the protocol employed, and then the 3D coordinates were checked for dropped-out markers. If there were any, they were connected linearly. Finally, the best trial record for each session was selected for the gait analysis.

From each trial, a heel-strike to heel-strike gait cycle was selected for both legs. Gait cycle was defined by identifying gait events known as heel-strike and toe-off, and the further analyses were performed using the biomechanical model contained in the gait analysis software packages, namely Kiss-GAIT and VCM. Graphs were then produced showing angles at the pelvis, hip, knee and ankle.

The three-dimensional parameters which were analyzed and compared include: pelvic tilt, obliquity and rotation angles, hip flexion-extension, abduction-adduction and rotation angles, knee flexion-extension, varus-valgus and rotation angles, ankle plantar-dorsiflexion angles and foot alignment and rotation angles. Moreover, time distance parameters were calculated and compared.

For each parameter, both systems retrieved the output that was normalized based on a full gait cycle. Kiss-GAIT normalized the gait data to 100 data points, whereas VCM normalized to 51 data points over stride.

Kinematic results obtained from the experiments were desired to plot on the same graph for the comparison. For this purpose, calculated and filtered joint angles were exported as TXT from the SAN (smoothed angle data) file of Kiss-GAIT, and calculated joint angles of VCM were taken from the Excel output file.

5.3.1 Comparison of Identical Motion Data

In order to compare the identical motion data, original 3D trajectory output file of one system was converted to the other system's file format, according to file conversion procedures explained in Section 5.2.1. Afterwards, 3D reconstructed data were given as an input into gait analysis software packages Kiss-GAIT and VCM separately. During kinematic analyses, same instants (same frame numbers) were identified as gait events in both software packages in order to prevent the differences that can arise from the analysis stage performed by the motion analyst.

According to Schwartz, Trost and Wervey (2004); variations in measured gait patterns arise from different sources. Some variations arise from experimental errors (extrinsic) and are candidates for quality improvement measures. Other variations occur naturally (intrinsic), and can only be measured and managed. Extrinsic errors can be further divided into intra-observer (inter-session) and inter-observer errors. Intrinsic errors are either intra-subject (inter-trial) or inter-subject errors.

By analyzing the same 3D motion data both intrinsic and extrinsic errors have been eliminated, and it is possible to investigate the parameters that affect the kinematic results due to model-based analysis methodology.

5.3.1.1 Experiment Performed in Ankara University-VICON System

An experiment was performed using Ankara University-VICON system according to KISS protocol. 3D trajectory output file of Vicon 370, so called C3D was converted to YOR file which is unique to KISS. The identical motion data were then processed using VCM and Kiss-GAIT gait analysis software packages separately. Accordingly, time distance parameters calculated by Kiss-GAIT and VCM were given in Table 5.1.

Table 5.1 Time distance parameters obtained from experiment performed in VICON system

Time-Distance Parameters	**Kiss-GAIT**		**VCM**	
	Right	Left	Right	Left
Step Length (m)	0.64	0.65	0.63	0.65
Stride Length (m)	1.28	1.29	1.29	1.29
Step Time (s)	0.56	0.54	0.57	0.58
Stride Time (s)	1.12	1.14	1.14	1.16
Cadence (steps/min)	106.00		105.24	103.44

As seen in Table 5.1, VCM calculates cadence for each leg separately, whereas Kiss-GAIT directly calculates the number of steps in a minute. Since temporal gait parameters can sometimes show significant asymmetry for right and left sides, VCM approach can be thought to be more reasonable.

There exists about 1 percent difference between temporal-distance parameters given in Table 5.1. Actually, it was anticipated that time distance parameters calculated by each system would be exactly the same, since motion data was same, and the timings of the gait events were particularly indicated at the same frame numbers. This difference may simply be due to rounding off, or there may be differences between the calculation methods of two systems.

For the purpose of examining the differences between calculation methods, stride time calculation was discussed as an example. Knowing the frame numbers related to the instant at which the gait cycle starts and ends, stride time can be easily calculated using the Equation 5.4.

$$StrideTime = \frac{EndCycle - StartCycle}{VideoFrameRate} \tag{5.4}$$

A single stride had been analyzed for each leg, and the timings of first and second heel strikes were as given in Table 5.2, representing the start and end of the gait cycle, respectively. Inserting the known values into the Equation 5.4, stride time for right and left leg were calculated and presented in Table 5.2.

Table 5.2 Stride Time Parameters

	Start Cycle	End Cycle	Stride Time
Right	58	115	1.14
Left	86	144	1.16

Calculated values in Table 5.2 verified that VCM uses Equation 5.4 for stride time calculations, however Kiss-GAIT calculates the stride time using the Equation 5.5.

$$StrideTime = \frac{EndCycle - StartCycle - 1}{VideoFrameRate} \tag{5.5}$$

In the calculation of step length and stride length, distance moved in direction of progression from start to end of gait cycle must be determined from the coordinates of foot markers. Probably, these two software packages take different markers as reference; one uses the toe marker for instance, whereas the other uses the ankle marker.

Another output of gait analysis is the results related to joint kinematics. As previously described in Section 3.2.4, 19 markers were placed on specific locations in static trial according to KISS data collection protocol. Furthermore, KISS protocol uses 13 markers, 7 of which are stick markers in gait trial. In order to be analyzed the same motion data in VCM, which employs different protocol again described in Section 3.2.4, only the trajectories of 15 markers out of 19 markers were considered as static trial data. In other words, outer markers of centering devices were ignored in the analysis performed in VCM.

Original plots of joint angles produced by Kiss-GAIT and VCM were given in Appendix B.1. Kinematic results of the experiment performed in Ankara University-VICON system according to KISS protocol, which were obtained from Kiss-GAIT and VCM, were plotted on the same graphs showing the effect of two different gait analysis methodologies (Figure 5.2 – 5.21).

In all plots, entire gait cycles of each leg with heel strike at 0 percent were presented. The abscissa represents percentage of the gait cycle, and values of joint angles are in degrees. Solid lines denote the Kiss-GAIT results, whereas cross-marked lines denote VCM results for the same motion data.

When making comparisons of the right and left sides, it is important to note that the plots do not represent events that have occurred at the same point in time, that is, heel contact of the right and left foot do not occur simultaneously. In order to plot right and left side data on the same horizontal axis, all data is normalized to 100% of gait cycle and then plotted together. Bilateral comparisons can be made more easily by using this format. Due to this fact, time information is lost, however can be obtained using the temporal distance information such as given in Table 5.1.

Figure 5.2 – 5.6 shows pelvic motion which is measured as a rotation of the pelvic segment with respect to a global coordinate system (laboratory). As seen in three pelvic plots, Kiss-GAIT calculates a single angle for the pelvis, considering the fact that pelvis is a single rigid body, and assuming the motion of the right side will be equal to the motion of the left side.

Because the pelvis is a rigid structure, the rotations occur alternately at each hip, bringing the pelvis forwards as the hip flexes and backwards as it extends. And also, being a normalized plot, angles for left and right side do not occur at the same instant of time. Therefore, right and left side motion of the pelvis should be plotted separately.

When interpreting right and left pelvic data on one plot that is normalized to 100% gait cycle, the motion of one side for a healthy individual should mirror the motion of the other. On the other hand, for the pathological cases, angles of right and left side of pelvis may be completely different. For instance, there can be an asymmetric pelvis with the right side held posterior to the left throughout the gait cycle.

Figure 5.2 shows the variation in the pelvic tilt angle. Pelvic tilt occurs in the sagittal plane and it is the inclination (typically forward) of the pelvic plane as viewed by an observer looking along a line connecting the ASISs. Pelvic tilt angle of the right side is almost identical. Very slight difference exists, because Kiss-GAIT normalizes the gait data to 100 data points, whereas VCM normalizes to 51 data points over stride.

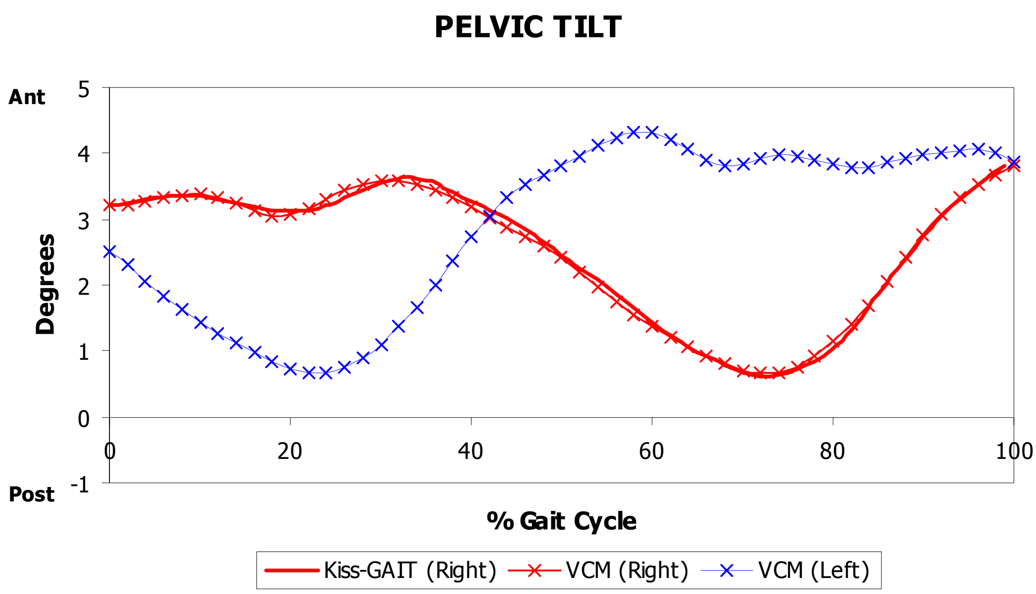


Figure 5.2 Comparison of Results for Pelvic Tilt Angle

Figure 5.3 shows pelvic obliquity angle which refers to the angle of inclination of the right and left ASIS in relation to the horizontal as viewed from front. In this plot, red lines represent the same angle; however they are symmetric with respect to the x-axis.

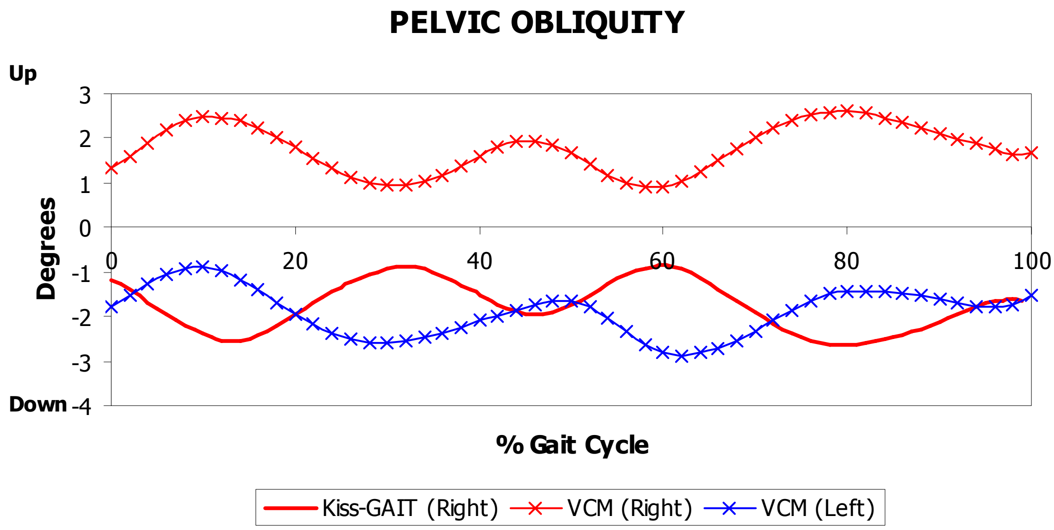


Figure 5.3 Comparison of Results for Pelvic Obliquity Angle

This symmetry can be explained that Kiss-GAIT and VCM use different sign conventions for pelvic obliquity angle. For pelvis coordinate system, rotation about the antero-posterior axis represents obliquity (Figure 5.4). Therefore, an upward motion of the pelvic plane is taken as positive based on the right hand rule.

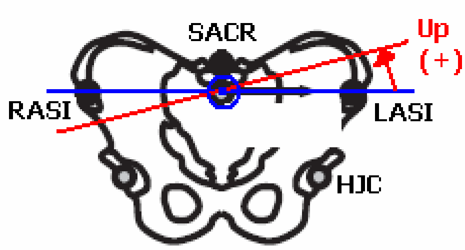


Figure 5.4 Pelvic Obliquity Angle (Front view)

On the other hand, when describing joint angles, it is important to adopt the sign convention which is consistent with its clinical use. Pelvic upward motion is always treated as positive in clinical literature as well.

Most probably, Kiss-GAIT assumes the downward motion as positive. Accordingly, if Kiss-GAIT graph is multiplied by -1, then pelvic obliquity angles for right side of the pelvis would be same for both systems (Figure 5.5).

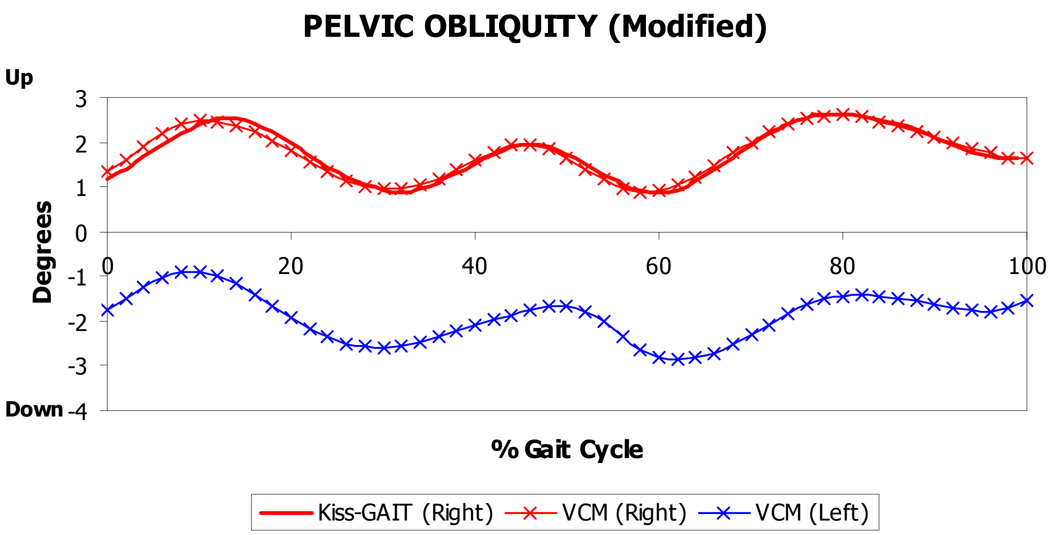


Figure 5.5 Comparison of Results for Pelvic Obliquity Angle (Modified)

Figure 5.6 illustrates the pelvic rotation which is the motion of the ASIS to ASIS line relative to a line perpendicular to the direction of progression as viewed by an observer whose site line is perpendicular to the pelvic plane. For this motion Kiss-GAIT and VCM has given exactly the same plots.

Pelvic plots showed that pelvic angles in three directions are almost identical. Because, pelvic motion is the rotation of the pelvic segment with respect to the global coordinate system, which is laboratory-fixed, and the coordinate system of the pelvis is described using only the external markers whose trajectories are measured directly by the optical motion capture system.

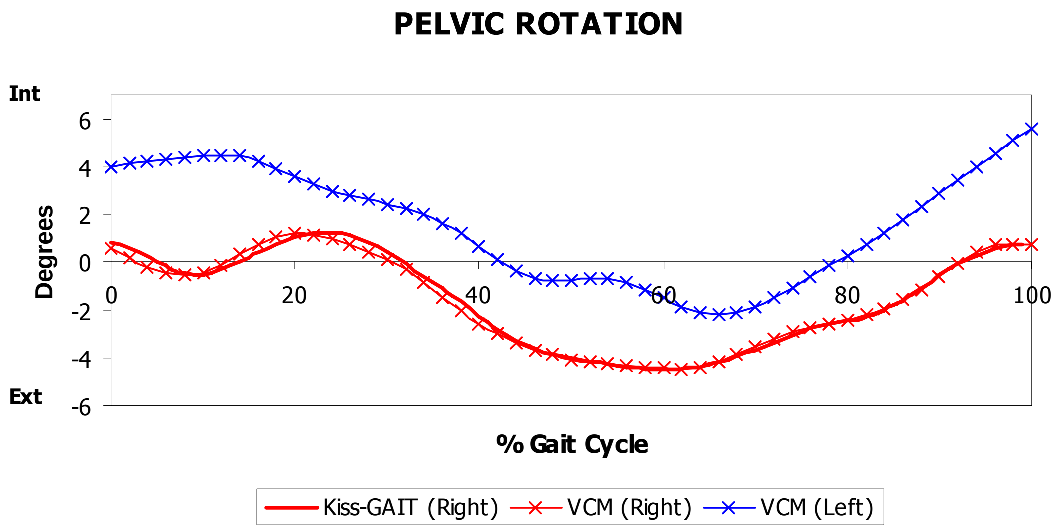


Figure 5.6 Comparison of Results for Pelvic Rotation Angle

However, in the hip joint motion, the case is different. Three rotational components of hip motion reflect the motion of the thigh segment relative to the pelvis. Anatomical coordinate system for thigh is defined using the estimated HJC (hip joint center), KJC (knee joint center) and knee flx/ext axis. HJC and KJC are internal landmarks, and they are estimated using different approaches. Therefore, any difference in these estimated anatomical landmark (AL) locations consequently influences the anatomical coordinate system definition, and then the calculated joint angle.

Kiss-GAIT estimates HJC using the method of Davis et al. (1991), whereas VCM uses the method of Bell, Brand and Pedersen (1990), which has been previously described in details in Section 3.3.4. In Davis's method, location of the HJC is calculated from the positions of pelvic markers by using a regression equation developed through radiographic examination of 25 hip studies. According to Bell's method, HJC is located from ASIS by certain distances defined by the percentages of Inter ASIS distance, which were obtained through radiographs of 31 normal adult skeleton pelves.

The accuracy and precision with which the HJC location is estimated are crucial for error propagation to the kinematic measurements of the hip and knee joints

(Kadaba, Ramakrishnan, and Wootten, 1990; Ramakrishnan and Kadaba, 1991; Pennock and Clark, 1990; Croce, Leardini, Chiari and Cappozzo, 2005).

Kadaba et al. (1990) investigated the effects of the erroneous determination of the HJC location. When the HJC location was made to vary analytically over a 20 mm range in all directions, they observed an offset in joint kinematics curves but not an effect on the relevant patterns throughout the gait cycle.

Studies carried out using different approaches reported a common conclusion. When joint rotations occur mainly in a single plane, minor rotations out of this plane are strongly affected by errors introduced at the AL identification level.

Cheze (2000) performed a test with the goal of identifying the joint kinematics sensitivity to AL location determination. Unfortunately, the study did not report the details of the analysis methods. However, the results showed that int/ext rotations were the most sensitive to AL instantaneous position errors.

Another internal landmark used for the definition of anatomical coordinate system for thigh is the KJC. KJC estimation methods used in Kiss-GAIT and VCM are also different (Section 3.3.4). VCM estimates KJC from estimated HJC and the external markers attached on knee and thigh geometrically by the help of the "CHORD" function. Therefore, correct placement of knee and thigh markers are very critical in VCM protocol as comprehensively explained in Section 3.2.4.1 for the correct estimation of KJC and knee flx/ext axis.

In Kiss-GAIT protocol, KJC is determined relative to the positions of the existing markers during the static shot. First, the unit vector along the knee flx/ext axis is defined from outer knee centering device (KCD) marker to inner KCD marker. Then, KJC is estimated based on the knee axis direction and coronal plane knee width measurement obtained during the clinical examination. Therefore, to locate KCD precisely is very critical in Kiss-GAIT protocol. Any misalignment in KCD influences the definition of knee flx/ext axis, and subsequently the definitions of the anatomical coordinate system and resulting joint angle.

Schache, Baker, and Lamoreux (2006) emphasized that misalignment of knee flx/ext axis can cause the propagation of errors proximally. The neutral position of hip axial rotation is dependent upon the orientation of the knee joint flx/ext axis. Errors in defining this axis manifest as offsets in the hip axial rotation kinematic profile. Thus, errors in defining the knee joint flx/ext axis can cause considerable variability in hip axial measurements during gait. Schache et al. (2006) pointed out that this is a less acknowledged side effect but can be one of greater clinical concern.

Figure 5.7 – 5.9 shows hip motion which is measured as a rotation of the thigh segment with respect to pelvis coordinate system. Figure 5.7 shows the hip flexion/extension angle which is the relative angle between the long axis of the thigh and a perpendicular to the pelvic plane as viewed by an observer looking along a line connecting the ASISs. Hip flx/ext angles obtained by Kiss-GAIT and VCM are almost identical.

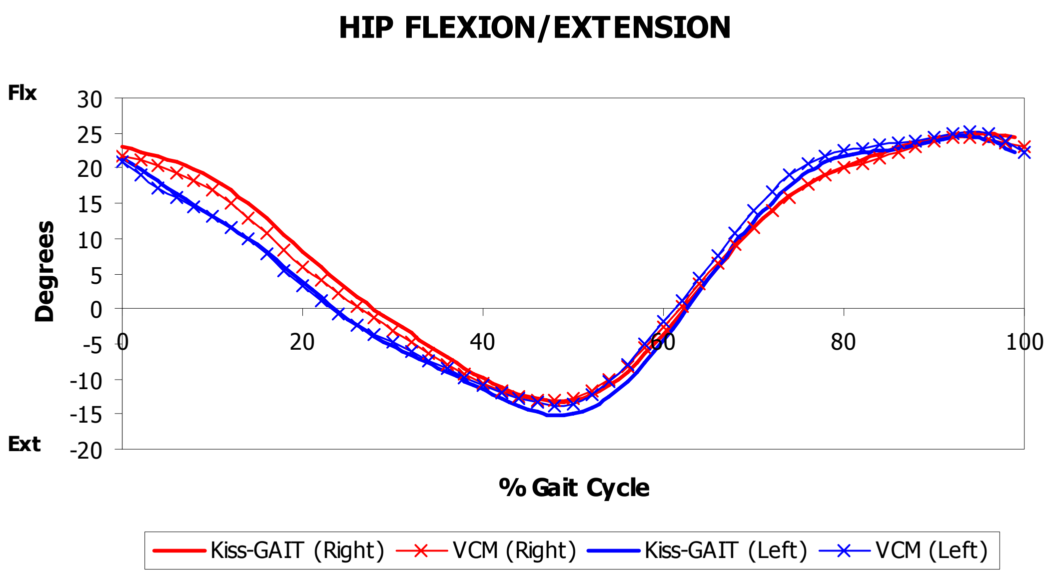


Figure 5.7 Comparison of Results for Hip Flexion/Extension Angle

Figure 5.8 shows the hip abduction/adduction angle which is the relative angle between long axis of the thigh and a perpendicular to the pelvic plane as viewed from the front of and in the pelvic plane. Results obtained by Kiss-GAIT and VCM for hip abd/add angles are almost identical.

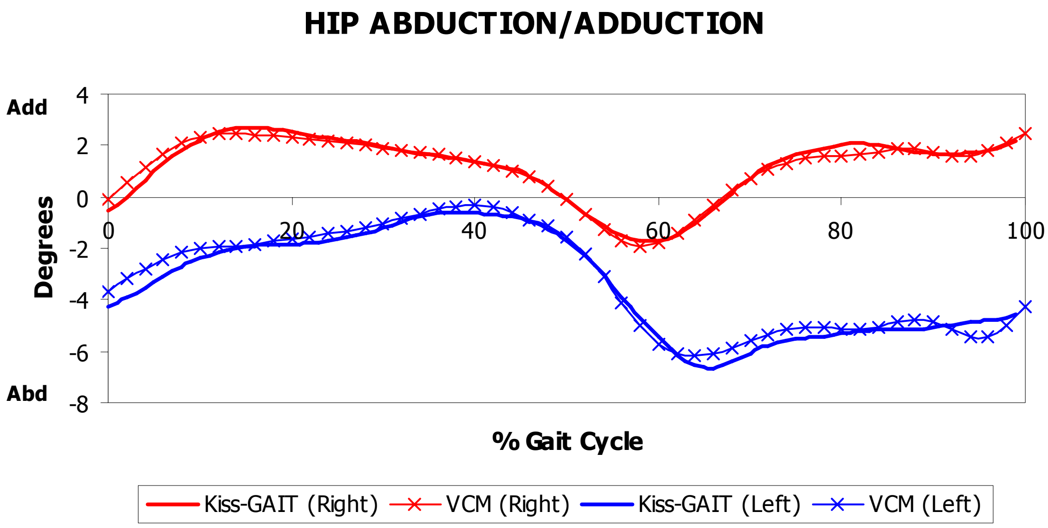


Figure 5.8 Comparison of Results for Hip Abduction/Adduction Angle

Figure 5.9 shows the hip internal/external rotation which is the motion of the medial-lateral axis of the thigh with respect to the medial-lateral axis of the pelvis within the transverse plane as seen by an observer positioned along the longitudinal axis of the thigh.

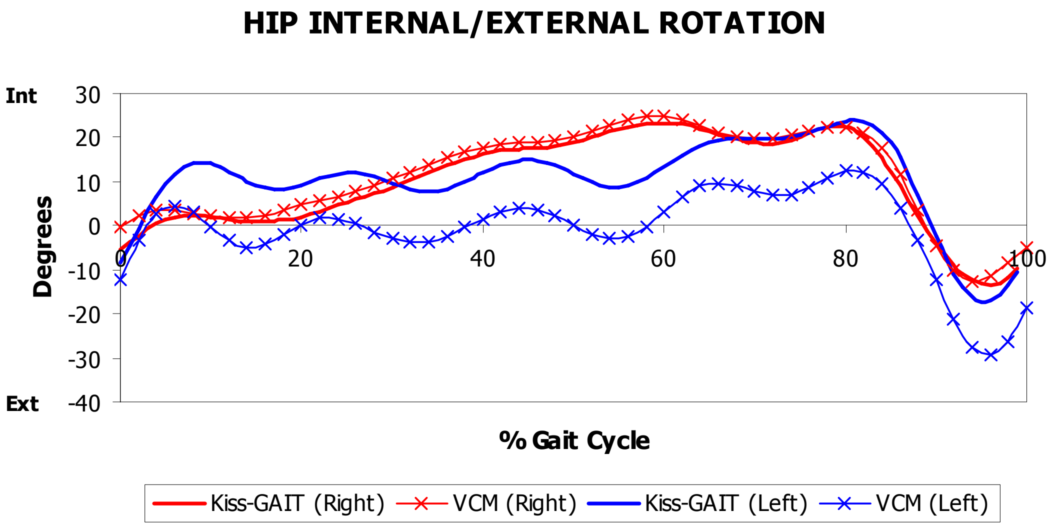


Figure 5.9 Comparison of Results for Hip Internal/External Rotation Angle

As seen from Figure 5.9, right hip int/ext rotation angles computed by two programs are almost identical, except slight differences at the beginning and end points of the graphs. This difference can most likely be attributed to each program's different smoothing and normalization techniques.

Int/ext rotation angle plots for left hip have a significant difference. Considering the above discussion, significant difference between the results regarding the int/ext rotation angles for left hip may be due to the estimation of left HJC location, errors may propagate downstream accordingly and seen only in the int/ext rotation plots. However, it does not seem to be possible for this case, since prediction methods are used for HJC center estimation. Therefore, if left HJCs were estimated differently, same difference would display in right hip as well.

Most probably, this difference results from the estimation of knee flx/ext axis. As explained before, Kiss-GAIT system estimated the knee axis based on the knee centering device placement in static shot. Line along two markers on the KCD determines the knee axis. On the other hand, VCM can determine the knee axis and knee joint center with a geometrical approach, only using the external markers attached on the thigh and knee. Therefore, misalignment of KCD in left leg most probably caused the difference in Figure 5.9.

Figure 5.10 – 5.13 are the graphs for knee motion reflecting the motion of the shank segment relative to the thigh segment. As previously discussed, thigh coordinate system is defined by estimated HJC, KJC and knee flx/ext axis. Croce et al. (2005) advocated that the effects of erroneous HJC location determination on knee angles were found to be negligible.

Anatomical coordinate system for shank is defined using the estimated KJC, AJC and ankle flx/ext axis. Kiss-GAIT and VCM estimate the knee and ankle joint centers with different approaches previously described in the above discussions and in Section 3.3.4. Consequently, the position and orientation of the coordinate systems embedded in knee and ankle joints will be found different by each program.

Schache et al. (2006) asserted that estimation of knee joint flx/ext axis is prone to considerable error. If the estimated knee joint flx/ext axis is misaligned, errors propagate downstream to the knee valgus/varus and int/ext rotation angles. This is typically described as knee joint angle crosstalk.

Piazza and Cavanagh (2000) performed a test for the estimation of the crosstalk among the angular components used to describe knee kinematics. They concluded that joint kinematic representation is extremely sensitive to rotation axis location in space, and recommended a limited use of minor angle data.

Croce et al. (2005) estimated the propagation of AL position precision to joint kinematics by simulating the joint movement. Results of their study show that int/ext rotation components were the least precise. Precision propagation to knee abd/adduction and int/ext rotation angles was shown to be dependent on the degree of knee flexion. The values of both ab/adduction and int/ext rotation angles were considered to be large enough to affect the reliability of the intrinsically small values of these angles. The same did not hold true for hip and ankle.

Figure 5.10 shows the knee flx/ext angle which is the relative angle between the long axis of the thigh and shank segments as viewed by an observer looking along the knee flx/ext axis.

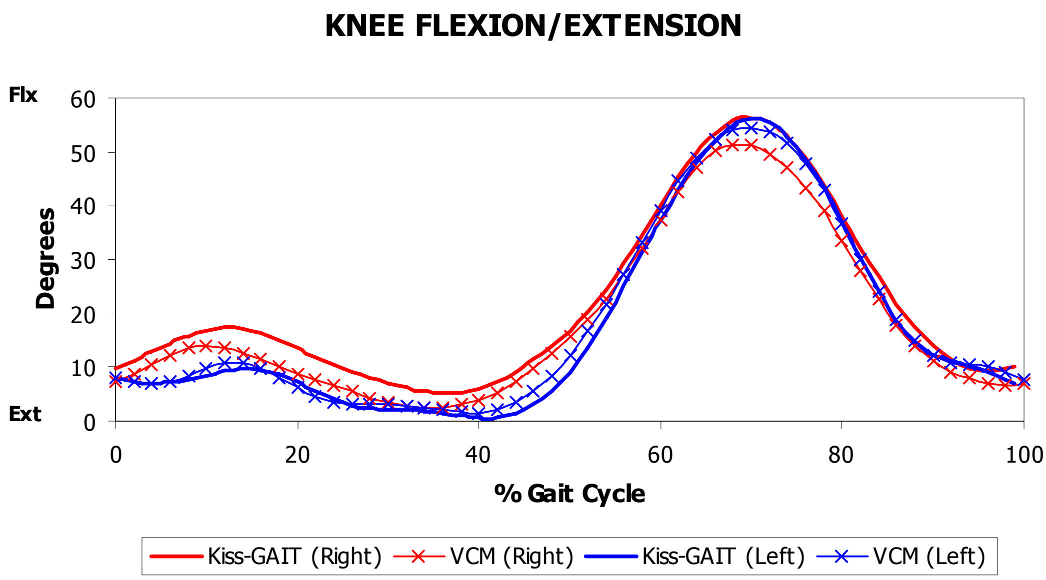


Figure 5.10 Comparison of Results for Knee Flexion/Extension Angle

As seen from Figure 5.10, knee flexion/extension angles obtained by Kiss-GAIT and VCM are almost identical. Figure 5.11 shows knee valgus/varus angle which is the relative angle between the long axis of the thigh and shank segments as viewed from the front of and in the thigh plane.

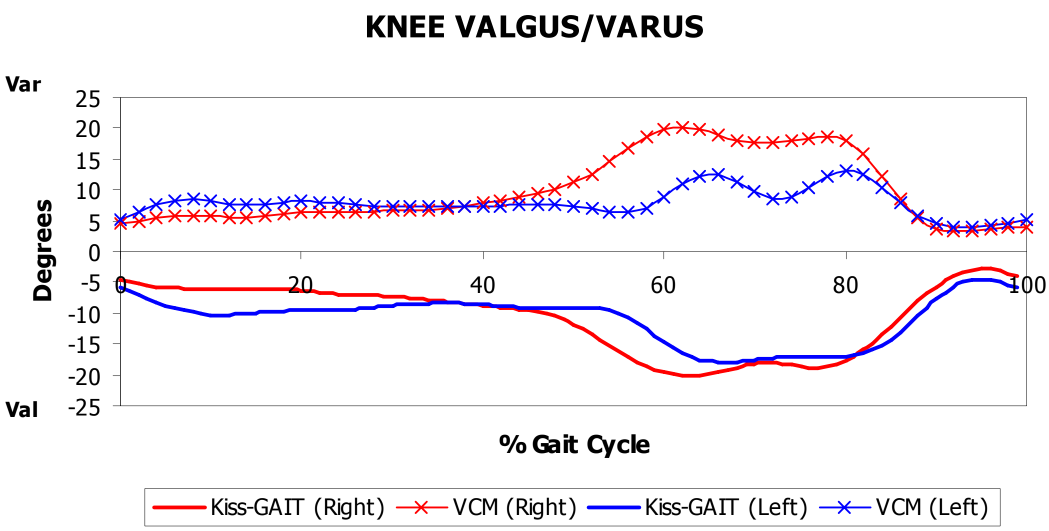


Figure 5.11 Comparison of Results for Knee Valgus/Varus Angle

Figure 5.11 clearly indicates a difference in sign convention used in Kiss-GAIT and VCM for knee valgus/varus angles. Therefore, Kiss-GAIT graph was multiplied by -1, and the resulting graph was presented in Figure 5.12.

After all, the left side has again a considerable difference, as in the case of hip int/ext rotation angles (Figure 5.9). This similarity in the left side angles strengthens the possibility that KCD was imprecisely located on the left knee joint of the subject by the experimenter. Hence, differences were arisen between the outputs of Kiss-GAIT and VCM which use different methods to determine the orientation of knee axis.

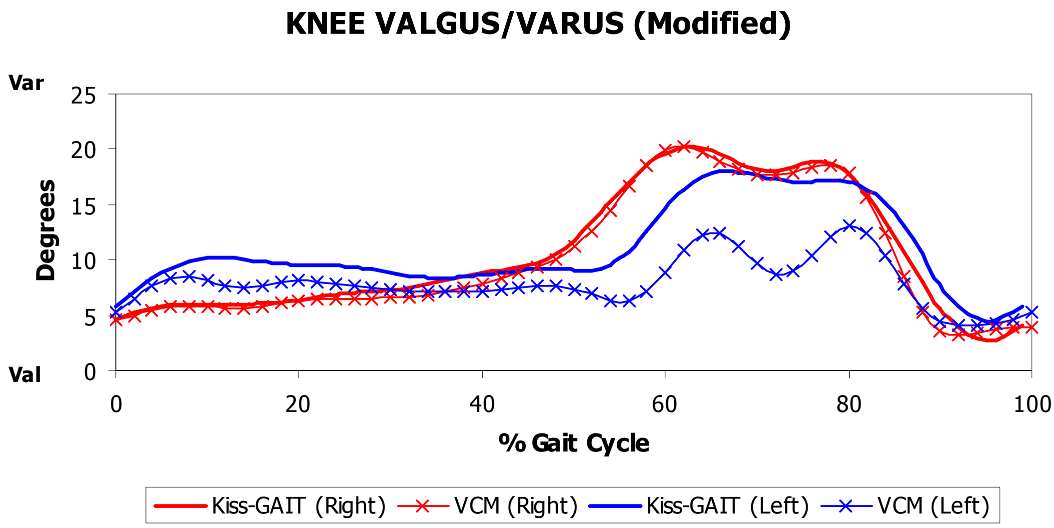


Figure 5.12 Comparison of Results for Knee Valgus/Varus Angle (Modified)

Figure 5.13 shows the knee int/ext rotation which is the motion of the shank (as defined by the ankle dorsi/plantar flexion axis) relative to the knee flx/ext axis line as viewed by an observer above the thigh plane.

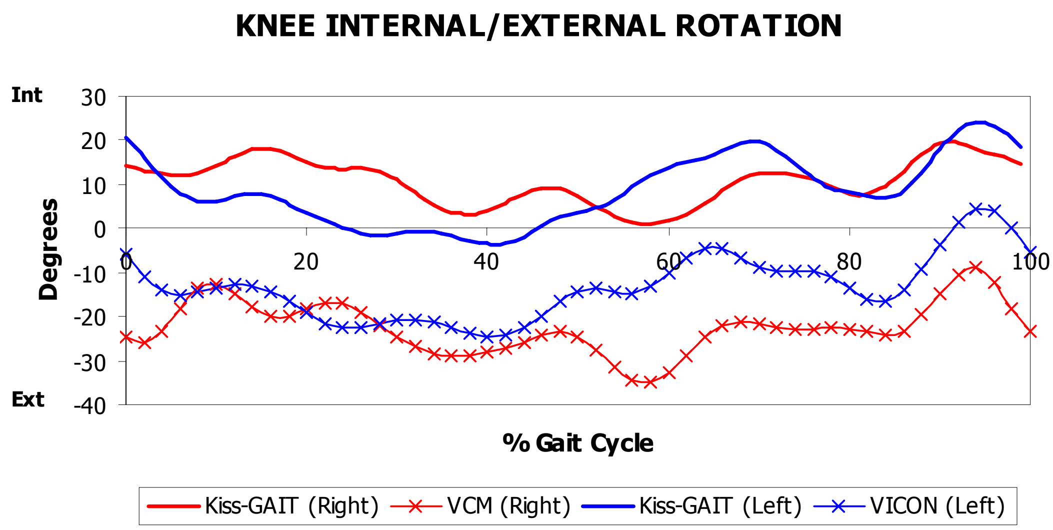


Figure 5.13 Comparison of Results for Knee Internal/External Rotation Angle

In Figure 5.13, an offset exists between the lines that represent the same angle. The difference between the position and orientation of anatomical coordinate system embedded in knee joint may cause this offset, as also underlined in the above discussions (Schache et al. 2006; Piazza and Cavanagh, 2000; Croce et al., 2005).

In order to eliminate this offset, curves were shifted. As it is seen from Figure 5.14, there are still differences in the trends of the curves. Any difference until this stage may cause this difference, since errors may propagate downstream and proximal errors give rise to distal errors. Also, being the last rotation in Euler angle sequence, int/ext rotation components were the least precise, since any error propagates from flx/ext axis to int/ext axis.

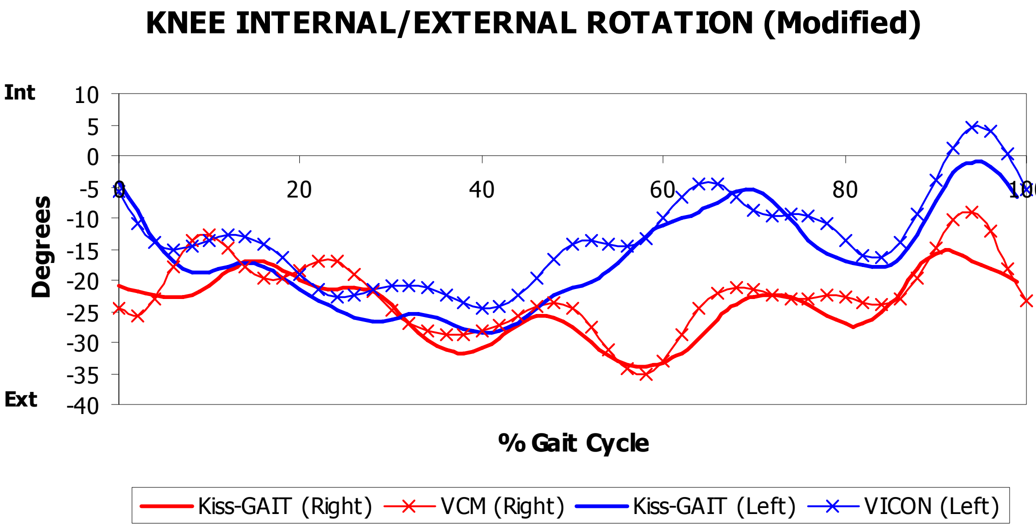


Figure 5.14 Comparison of Results for Knee Internal/External Rotation Angle (Modified)

It is evident from the comparison of the plots that the calculated joint angles in the sagittal plane exhibited good agreement between the two gait analysis software. However, the angles in the coronal and transverse planes had more or less difference.

Güler (1998) concluded that the angles in coronal and transverse planes were more prone to errors due to low signal-to-noise ratio. He added that any alignment errors in the reference position used to calculate the transformation between the technical and anatomical frames might have introduced a constant shift into the angle curves.

Figure 5.15 – 5.21 illustrate the graphs of ankle angles reflecting the motion of the foot segment relative to the shank segment.

Figure 5.15 shows ankle dorsi/plantarflexion angle which represents the motion of the plantar aspect of the foot within the sagittal plane as seen by an observer positioned along the medial-lateral axis of the shank.

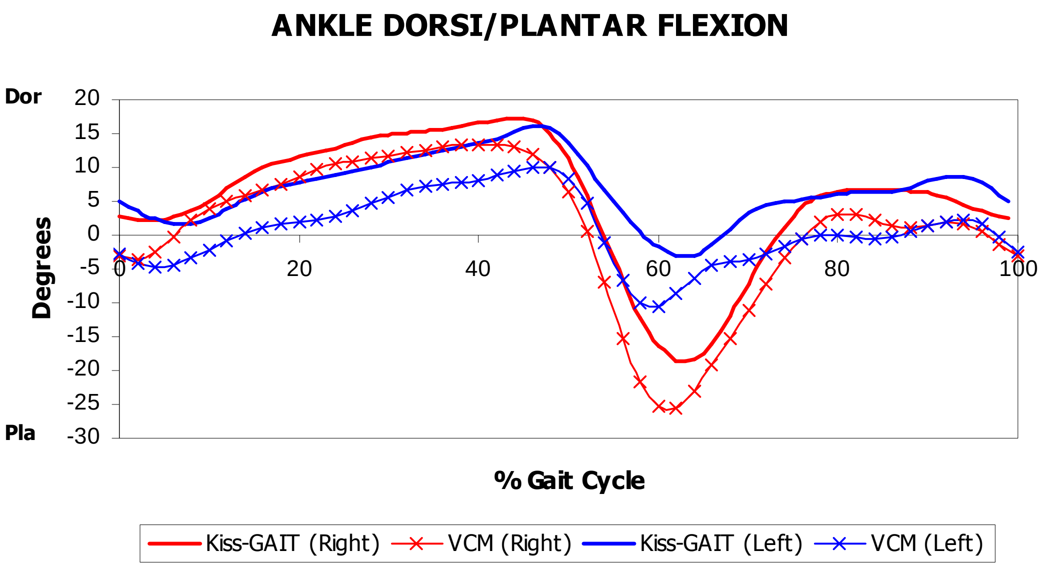


Figure 5.15 Comparison of Results for Ankle Dorsi/Plantar Flexion Angle

Close inspection of the plots in Figure 5.15 reveals that actually curves do match; the errors are small shifts of the curve horizontally and/or vertically. These differences most probably result from the differences in ankle axis determination caused by the misalignment of ankle centering device. In order to eliminate the differences caused by ankle axis determination, Kiss-GAIT curves were shifted by a certain amount (Figure 5.16).

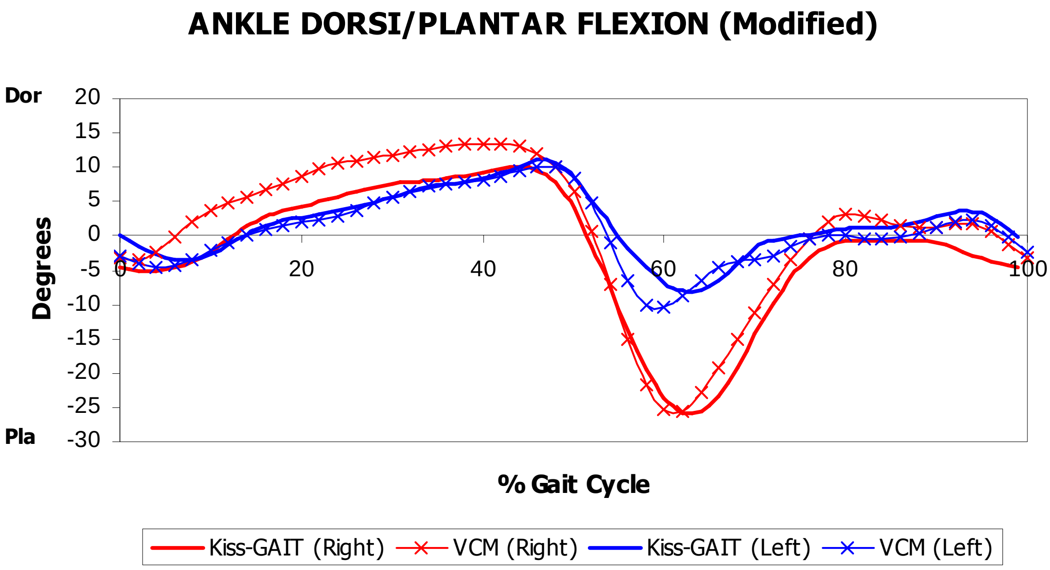


Figure 5.16 Comparison of Results for Ankle Dorsi/Plantar Flexion Angle (Modified)

Figure 5.17 shows the internal/external rotation at the ankle joint. Error propagation from proximal to distal influences the ankle kinematics most. Smaller changes proximally result in correspondingly greater changes in the kinematics of the distal segments.

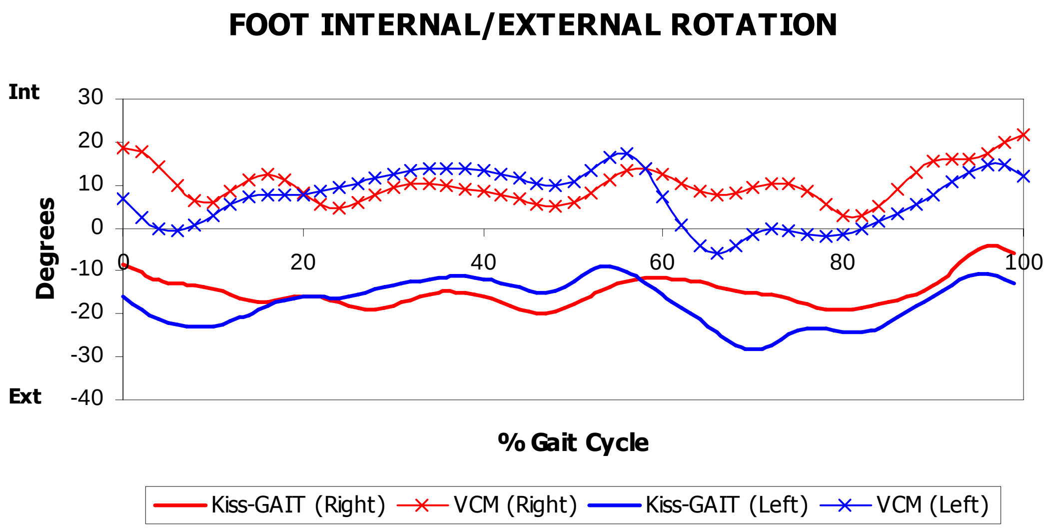


Figure 5.17 Comparison of Results for Foot Internal/External Rotation Angle

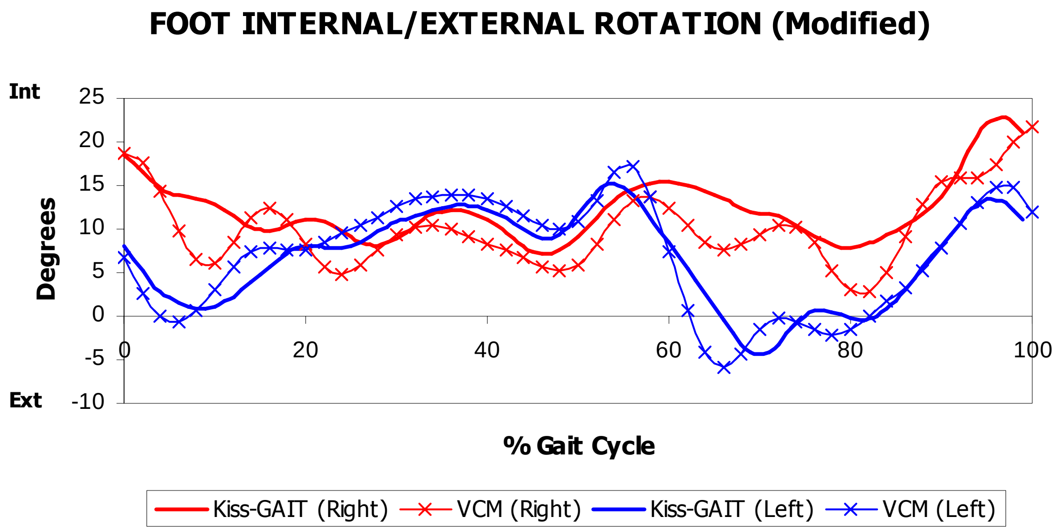


Figure 5.18 Comparison of Results for Foot Internal/External Rotation Angle (Modified)

Figure 5.20 shows the foot progression angle which is the angle between the long axis of the foot (AJC to toe external marker) and the direction of progression as seen from above. Foot progression measure the alignment of the foot as an absolute angle in the ground plane as it is represented in Figure 5.19.

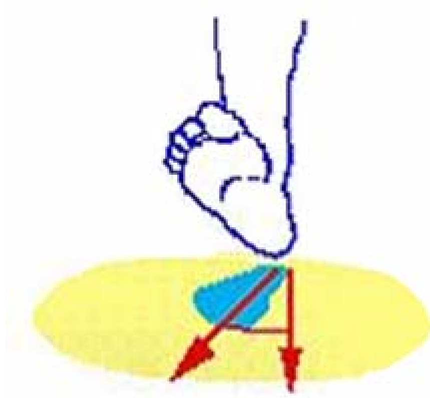


Figure 5.19 Foot Progression Angle

In the original output plots of KISS, foot alignment angle curves are not plotted for the swing phase. Because when the foot is not in contact with the ground, this angle has not been found meaningful.

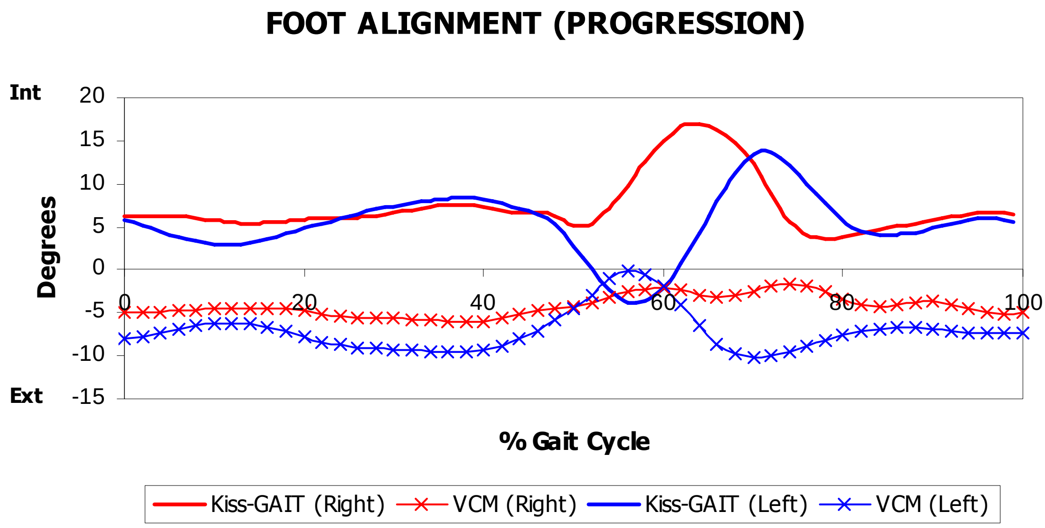


Figure 5.20 Comparison of Results for Foot Alignment Angle

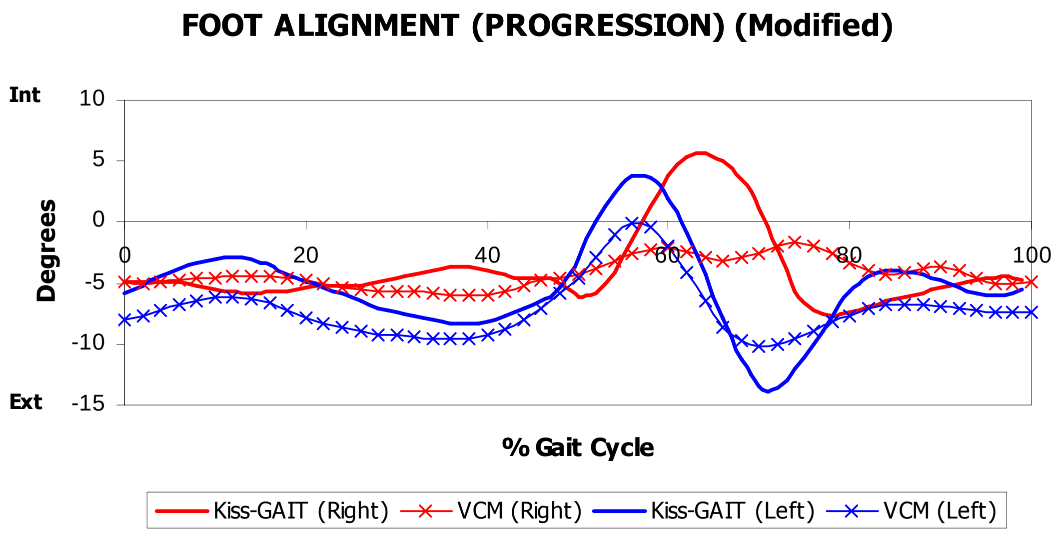


Figure 5.21 Comparison of Results for Foot Alignment Angle (Modified)

5.3.1.2 Experiment Performed in METU-KISS System

An experiment performed with METU-KISS system according to KISS protocol was analyzed using both Kiss-GAIT and VCM. Time distance parameters calculated by two programs were given in Table 5.3.

Table 5.3 Time distance parameters obtained from experiment performed in METU-KISS

Time-Distance Parameters	**Kiss-GAIT**		**VCM**	
	Right	Left	Right	Left
Step Length (m)	0.65	0.63	0.62	0.63
Stride Length (m)	1.27	1.26	1.26	1.25
Step Time (s)	0.56	0.56	0.60	0.60
Stride Time (s)	1.16	1.16	1.20	1.20
Cadence (steps/min)	103.50		99.96	99.96

Kinematic results of the experiment performed in METU-KISS system according to KISS protocol show similar differences with the experiment performed in VICON system using the same protocol. Therefore, results were presented in the Appendix B.2 and the differences between the results are not discussed again.

5.3.2 Comparison of Kiss-GAIT and VCM Data Collection Protocols

In order to compare the different data collection protocols, two sessions were performed in the Ankara University-VICON gait analysis system. Kiss-GAIT marker set, including stick markers and centering devices were placed on the subject in the first session. After trials were captured, Kiss-GAIT markers were removed and VCM markers were attached on the same locations.

Data captured in both sessions reconstructed by VICON 370 and analyzed in VCM. Accordingly, results calculated by VCM were given in Table 5.4 and Appendix B.3.

Table 5.4 Time distance parameters calculated by VCM

Time-Distance Parameters	**Kiss-GAIT Protocol**		**VCM Protocol**	
	Right	Left	Right	Left
Step Length (m)	0.63	0.65	0.65	0.69
Stride Length (m)	1.29	1.29	1.33	1.34
Step Time (s)	0.57	0.58	0.57	0.58
Stride Time (s)	1.14	1.16	1.14	1.16
Cadence (steps/min)	105.24	103.44	105.24	103.44

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 GENERAL CONCLUSIONS

This work is concerned with the comparison of two gait analysis systems. Two building blocks for this overall work involve evaluation of the performance of data acquisition system and model-based gait analysis methodology of two gait analysis systems, METU-KISS and Ankara University-VICON systems, separately and independently.

This study was intended to measure the performance of the two systems under identical conditions. For assessing the data acquisition performance of the systems, standard, precisely known motion of a physical pendulum was utilized to determine the accuracy of relative distance measurement and to estimate the noise in the data. Such a test enabled to compare the two systems with using the same protocol, and as a result, at least a general idea for the relative performance of each system was provided.

However, whilst providing information about spatial accuracy, this approach does not test the modeling software of the two systems, the validity of which is crucial for clinical studies. Therefore, in the second step of this thesis, model-based gait analysis methodology of the systems were compared and evaluated using the identical motion data in order to eliminate the differences due to data acquisition instrument and software. By analyzing the same motion data on each system, a direct comparison can thus be made between the software responsible for calculating joint kinematics.

Two gait analysis software packages, Kiss-GAIT and VICON Clinical Manager (VCM), being the subject of discussion in this thesis utilize the same biomechanical model, and this model requires an external marker set to calculate joint kinematics. Although the Helen Hayes hospital marker set is used in the two software packages, the methods for calculating the joint centers, segment orientations, as well as the joint angles differ.

The primary purpose of this study was to document discrepancies between the kinematic results obtained by each gait analysis software package, and to address possible reasons for these differences.

The kinematic results obtained by the two software packages were very comparable for most of the plots. Joint angles for pelvis were almost identical, and the joint angles in the sagittal plane matched quite well. The rotation plots had the greatest difference being the last rotation in the Euler sequence. The ankle plots did not fair as well. These results confirmed that Kiss-GAIT and VCM use a hierarchical biomechanical model, so that errors propagate "downstream" from proximal to distal.

The differences observed for joint angles may be influenced by the methods of calculating the joint angles and the different filtering algorithms used. However, the effect of these differences is assumed to be small, but they may contribute to the differences observed. On the other hand, different methods of calculating segment axes and joint centers probably have a larger effect on the differences.

Results of this study indicated that the definitions of local coordinate systems used to express the rotation angles have a critical effect upon the calculated joint angles. Small differences in the position and orientation of segment coordinate systems can yield large differences in joint angle calculations.

Kiss-GAIT and VCM estimate hip joint center based on prediction methods proposed by Davis et al. (1991) and Bell et al. (1990), respectively. It was shown that these methods give very close results or the differences in estimating hip joint center location do not affect the joint kinematics considerably.

On the contrary, estimation methods regarding the knee and ankle joint center locations considerably influence the joint kinematics. Results showed that Kiss-GAIT model is extremely sensitive to correct alignment of the centering devices, and any alignment errors introduce a constant shift into the angles.

The findings of this study demonstrated that one of the most important problems in gait analysis is the lack of a standardized gait analysis protocol. Kadaba et al. (1990) stated that effective use of movement analysis in a professional context depends on a universal agreement on parameter definitions, conventions and terminology. This will facilitate information integration and allow for a direct interpretation and comparison of data obtained at different laboratories.

The Standardization and Terminology Committee of the International Society of Biomechanics has undertaken considerable efforts in recent years to develop a set of standards for reporting joint motion. They have published ISB recommendations for the definitions of global reference frames, joint coordinate systems and anatomical landmarks so as to encourage the use of these recommendations. It is hoped that adopting a set of widely accepted standards will lead to better communication among researchers and clinicians.

It should be noted that extension to the present document in the future including the recommendations for joint center estimation methods would be useful to compare the data captured at different laboratories. Brand and Crowninshield (1981) pointed out that if the gait analysis community could achieve to standardize data collection and reduction techniques employed in gait analysis laboratories, gait analysis may be accepted as a diagnostic tool and not just an evaluation tool.

6.2 FUTURE WORK

This thesis gives much optimism to the idea of multi laboratory collaborations. Henceforward, gait analysis results from other C3D compatible software packages can be compared with those of Kiss-GAIT and VCM.

Kinematic results were only computed and compared in this thesis. Results based on kinetic data should also be compared in the future in order to evaluate the effects of different methods of estimating body segment parameters.

The present work discussed the discrepancies between systems in natural gait, which is a relatively planar movement. Having the ability to exchange motion data files between systems, gait pathologies, particularly those with frontal plane and rotational deformities can be examined in a further work.

One of the leading objectives of this thesis was to compare KISS with VICON, world leader in motion capture and analysis, and to assess the strengths and weaknesses of the two systems. The results of this effort have provided guidelines for future developments on the KISS system. A series of key recommendations to improve the performance of KISS system were outlined under three headings.

6.2.1 Data Acquisition

The primary need for the data acquisition system of KISS is a more comprehensive calibration procedure. KISS system currently utilizes a static calibration method involving four hanging rods with reference markers attached on each. Cameras view this array of static markers, and the calibration calculation is carried out independently for each camera. This method of calibration is difficult and time consuming, since preparation for this task requires considerable skill and takes much time.

Most of the 3D motion capture systems today support dynamic calibration having many advantages over using a fixed calibration object. Dynamic calibration works on a different principle. First, a short data capture is needed to determine the origin and direction of axes of the global reference frame. Then, a longer capture is made in which an operator moves around the measurement space, waving a wand on which two markers are mounted at a known separation. The wand calibration algorithm determines the parameters by minimizing the difference between the actual and calculated length of the wand over all image frames.

Dynamic calibration method determines system information such as focal length of lenses and the positions and orientations of cameras with respect to each other. It is important to note that correction of lens distortion can also be provided with dynamic calibration. By means of dynamic calibration, successively more accurate reconstructions of the markers on the moving wand are made, with the camera locations and orientations being calculated with increasing accuracy.

Wand calibration is easier to implement, and reduces set-up time. In fixed array calibration, number of markers limits the calibration accuracy, since each individual marker provides a control point for the parameter optimization. Instead, the wand calibration technique depends on the number of image frames collected.

Before all that, a quick recovery is needed for the data acquisition system of KISS. Linearization must be done immediately, since pendulum tests in Chapter 4 indicated that KISS system exhibits high standard variations, and straight lines may appear curved even near the center of the calibration volume. Later in the future, it is strongly recommended that linearization process is repeated every six months or earlier if results deteriorate. Furthermore, markers must be occasionally recovered with reflective material because they have become dirty and lost their reflective power. Laboratory floor can be covered with a matte material in order to prevent reflection problems which cause difficulties especially in the calibration process.

6.2.2 Data Processing

Offline processing after 3D reconstruction of markers take much time in KISS system relative to VICON. Because on certain occasions, KISS system have some difficulty in tracking closely spaced markers, and resulting in a phenomenon known as a crossover. Sometimes the calculation produces trajectories for markers that are not really there; these are known as ghost markers. Sometimes a marker is obscured from view because of arm swings or poor performance of the fifth camera. This results in broken trajectories. In all these cases, the user interaction is needed for track editing.

The first opportunity for improvement would be to renew the fifth camera, or different camera configurations can be tried to decide optimal camera positions. Moreover, cameras can be mounted on sidewalls in order to maximize the length of the capture volume. Markers are sometimes blooming due to excessive brightness which can occur when a marker is very close to a camera. Since the length of the laboratory is fairly short, wall mounted cameras may be more effective. Hence, unintentional camera movements by a slight kick could have been prevented.

New methods for the spatial and temporal matching of the markers can be devised as a future work to reduce the number of ghost markers and gaps in the marker trajectories.

A stick figure representation can be introduced in order to facilitate the operator in labeling and track editing. Automatic or assisted labeling algorithms can be developed for reducing the operator assistance. After initial assignment of markers on the subject in static shot, software can then apply this autolabel calibration to that subject in subsequent trials. After this assignment, software would have the capability to reassign the markers by utilizing the adjacent frames and to fill the gaps automatically in case of any occlusion or crossover.

6.2.3 Data Analysis

This study concluded that sign convention of Kiss-GAIT for joint angles is not consistent with the conventional clinical understanding of the terms. The angles for pelvic obliquity and knee valgus/varus are needed to be multiplied by -1 for the consistency.

Anatomical landmark identification has a significant impact on the reliability of the gait analysis results. Improvements on the identification of anatomical landmarks reduce imprecision and enhance the reliability.

This study demonstrated that the accuracy of the knee and ankle joint center estimation is extremely sensitive to correct alignment of the centering devices used in KISS system. Moreover, placement of centering devices is not practical, and is highly dependent on the experimenter.

In Kiss-GAIT protocol, knee and ankle rotation axes are estimated once from the static shot data, and the relation of these axes to the surface markers is assumed to be constant throughout the gait cycle. On the other hand, VCM calculates these axes at each instant of time from gait trial data without making any assumption. Such an approach seems to be more realistic, and a new method for knee and ankle joint center estimation is required to be implemented into KISS gait protocol.

Hip joint center determination is another important factor that affects the performance of a gait analysis system. The location of the hip joint center is estimated using either a functional approach (Cappozzo, 1984; Shea et al., 1997; Leardini et al., 1999; Piazza et al., 2001) or a prediction approach (Bell et al., 1990; Davis et al., 1991).

The functional approach estimates the hip joint center as the pivot point of a three dimensional rotation between the femur and pelvis body segments. The prediction approaches use regression equations based on standardized pelvic geometry.

In most of the prediction approaches, regression coefficients have been obtained on relatively small sample sizes of adult males. The recommendation is to use the functional methods in order to accurately locate the hip joint center (Leardini et al., 1999; Wu et al., 2002; Besier et al., 2003).

Functional approach with specific optimization algorithms used to fit markers on the thigh to a sphere can be developed for Kiss-GAIT in order to reduce the variability of hip joint center definitions. Subjects have to perform an additional task for the determination of the hip joint center. This method is suitable when there is an adequate range of motion possible in the hip joint being analyzed. Alternatively, any of the prediction methods may be used and, in fact, are especially recommended in patients with restricted range of motion of the hip joint.

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APPENDIX A

PROGRAM CODES

A.1 TXT-TO-YOR CONVERTER PROGRAM – MAIN

```
/*
 * Ezgi.java
 *
 * Created on November 13, 2005, 4:54 PM
 */

package ezgi;

import java.io.*;
import java.util.Vector;
import javax.swing.*;
import java.awt.*;
import java.awt.event.*;
/**
 *
 * @author  caglar
 */
public class Ezgi extends JFrame implements ActionListener{

    JButton srcB, dstB, ok, cancel;
    JTextField srcT, dstT;

    /** Creates a new instance of Ezgi */
    public Ezgi() {
        super("");
        this.setSize(400, 130);
        this.setResizable(false);
        this.setBounds(400, 300, 400, 170);
        this.setDefaultCloseOperation(JFrame.EXIT_ON_CLOSE);

        JLabel srcL = new JLabel("Source File:");
        srcL.setBounds(0, 20, 100, 20);
        srcL.setHorizontalAlignment(SwingConstants.RIGHT);

        srcT = new JTextField();
        srcT.setBounds(120, 20, 200, 20);
```

```
    srcB = new JButton("...");
    srcB.setBounds(330, 20, 40, 20);

    JLabel dstL = new JLabel("Destination File:");
    dstL.setBounds(0, 50, 100, 20);
    dstL.setHorizontalAlignment(SwingConstants.RIGHT);

    dstT = new JTextField();
    dstT.setBounds(120, 50, 200, 20);

    dstB = new JButton("...");
    dstB.setBounds(330, 50, 40, 20);


    ok = new JButton("OK");
    ok.setBounds(100, 90, 80, 30);
    cancel = new JButton("Cancel");
    cancel.setBounds(220, 90, 80, 30);

    srcB.addActionListener(this);
    dstB.addActionListener(this);
    ok.addActionListener(this);
    cancel.addActionListener(this);

    //ActionListener
    Container contentPane = this.getContentPane();
    contentPane.setLayout(null);
    contentPane.add(srcL);
    contentPane.add(srcT);
    contentPane.add(srcB);
    contentPane.add(dstL);
    contentPane.add(dstT);
    contentPane.add(dstB);
    contentPane.add(ok);
    contentPane.add(cancel);

    //this.pack();
}

/**
 * @param args the command line arguments
 */
public static void main(String[] args) throws java.io.IOException{
    new Ezgi().show();
}

public void actionPerformed(ActionEvent e) {
    if(e.getSource() == srcB)
        this.src_actionPerformed();
    else if(e.getSource() == dstB)
        this.dst_actionPerformed();
    else if(e.getSource() == ok){
        try{
            this.ok_actionPerformed();
        }
```

```
        catch(IOException ex){
            ex.printStackTrace();
        }
    }
    else if(e.getSource() == cancel)
        this.cancel_actionPerformed();
}

private void src_actionPerformed(){
    try{
        JFileChooser chooser = new JFileChooser();
        int returnVal = chooser.showOpenDialog(this);
        if(returnVal == JFileChooser.APPROVE_OPTION){
            srcT.setText(chooser.getSelectedFile().getCanonicalPath());
        }
    }
    catch(IOException ex){
        ex.printStackTrace();
    }
}

private void dst_actionPerformed(){
    try{
        JFileChooser chooser = new JFileChooser();
        int returnVal = chooser.showSaveDialog(this);
        if(returnVal == JFileChooser.APPROVE_OPTION){
            dstT.setText(chooser.getSelectedFile().getCanonicalPath());
        }
    }
    catch(IOException ex){
        ex.printStackTrace();
    }
}

private void ok_actionPerformed()throws java.io.IOException{
    BufferedReader reader = new BufferedReader(new FileReader(srcT.getText()));
    FileOutputStream ostream = new FileOutputStream(dstT.getText());
    TTrack3D track;
    String initialString;
    Vector tracks = new Vector(1);

    ostream.write(0);
    ostream.write(0);
    ostream.write(0);
    ostream.write(0);
    ostream.write(100);
    ostream.write(0);
    ostream.write(0);
    ostream.write(0);

    int k = 0;
    while(true){
        while(true){
            initialString = reader.readLine();
            if(initialString == null || initialString.trim().length() != 0)
```

```
                break;
            }
            track = TTrack3D.create(initialString, reader);
            if(track == null)
                break;
            else{
                if(k==0){
                    int tcount = track.getCount();
                    ostream.write(tcount & 0xff);
                    ostream.write((tcount & 0xff00) >> 8);
                    ostream.write((tcount & 0xff0000) >> 16);
                    ostream.write((tcount & 0xff000000) >> 24);
                    ostream.flush();
                }
                //track.write(writer);
                tracks.add(track);
            }
            k++;
        }

        //k++;

        ostream.write(k & 0xff);
        ostream.write((k & 0xff00) >> 8);
        ostream.write((k & 0xff0000) >> 16);
        ostream.write((k & 0xff000000) >> 24);
        ostream.flush();

        for(int i=0; i<tracks.size(); i++){
            ((TTrack3D)tracks.get(i)).write(ostream);
            ostream.flush();
            //System.out.println(((TTrack3D)tracks.get(i)).getlabel());
        }

        JOptionPane.showMessageDialog(this, "Done");
    }

    private void cancel_actionPerformed(){
        System.exit(0);
    }

}
```

A.2 TXT-TO-YOR CONVERTER PROGRAM – TTRACK3D

```
/*
 * TTrack3D.java
 *
 * Created on November 13, 2005, 4:58 PM
 */

package ezgi;

import java.io.*;
```

```java
/**
 *
 * @author  caglar
 */
public class TTrack3D {

    private TTrackLabel label = null;

    private int stf = 0;

    private int count = 0;

    private TCoor3D pts = null;

    /** Creates a new instance of TTrack3D */
    private TTrack3D(TTrackLabel label, int stf, int count, TCoor3D pts) {
        this.label = label;
        this.stf = stf;
        this.count = count;
        this.pts = pts;
    }

    public static TTrack3D create(String initialString, BufferedReader reader) throws
IOException{
        if(initialString == null){
            return null;
        }

        int seq = Integer.parseInt(initialString);
        String label = reader.readLine();
        int stf = Integer.parseInt(reader.readLine());
        int count = Integer.parseInt(reader.readLine());
        TCoor3D tCoor3d = TCoor3D.create(reader, count);

        //System.out.println("seq: " + seq + " label: " + label + " stf: " + stf + " count: " +
count);

        return new TTrack3D(new TTrackLabel(label), stf, count, tCoor3d);
    }

    public String getlabel(){
        return this.label.toString();
    }

    public void write(FileOutputStream ostream) throws IOException{
        this.label.write(ostream);

        this.stf--; //by definition
        ostream.write(this.stf & 0xff);
        ostream.write((this.stf & 0xff00) >> 8);
        ostream.write((this.stf & 0xff0000) >> 16);
        ostream.write((this.stf & 0xff000000) >> 24);
        ostream.flush();

        ostream.write(this.count & 0xff);
```

```
        ostream.write((this.count & 0xff00) >> 8);
        ostream.write((this.count & 0xff0000) >> 16);
        ostream.write((this.count & 0xff000000) >> 24);
        ostream.flush();

        this.pts.write(ostream);
    }

    public int getCount(){
        return this.count;
    }

}
```

A.3 TXT-TO-YOR CONVERTER PROGRAM – TTRACKLABEL

```
/*
 * TTrackLabel.java
 *
 * Created on November 13, 2005, 4:59 PM
 */

package ezgi;

import java.io.*;
/**
 *
 * @author  caglar
 */
public class TTrackLabel {

    private String label = null;

    /** Creates a new instance of TTrackLabel */
    public TTrackLabel(String label) {
        this.label = label;
    }

    public void write(FileOutputStream ostream) throws IOException{
        int size = this.label.length();
        ostream.write(size);
        ostream.write(this.label.getBytes());
        for(int i=size; i<8; i++)
            ostream.write(0);
        ostream.flush();
    }

    public String toString(){
        return this.label;
    }

}
```

A.4 TXT-TO-YOR CONVERTER PROGRAM – TCOOR3D

```
/*
 * TCoor3D.java
 *
 * Created on November 13, 2005, 5:00 PM
 */

package ezgi;

import java.io.*;
/**
 *
 * @author  caglar
 */
public class TCoor3D {

    private Coor3D c3d[];

    /** Creates a new instance of TCoor3D */
    private TCoor3D(int count) {
        this.c3d = new Coor3D[count];
    }

    private void add(int index, Coor3D coor3d){
        this.c3d[index] = coor3d;
    }

    public static TCoor3D create(BufferedReader reader, int count)throws IOException{
        TCoor3D tCoor3d = new TCoor3D(count);
        Coor3D coor3d = null;
        for(int i = 0; i<count; i++){
            coor3d = Coor3D.create(reader.readLine());
            //System.out.println(coor3d);
            tCoor3d.add(i, coor3d);
        }

        return tCoor3d;
    }

    public void write(FileOutputStream ostream)throws IOException{
        for(int i=0; i<this.c3d.length; i++){
            this.c3d[i].write(ostream);
        }
    }

}
```

A.5 TXT-TO-YOR CONVERTER PROGRAM – COOR3D

```
/*
 * Coor3D.java
 *
```

```
 * Created on November 13, 2005, 5:01 PM
 */

package ezgi;

import java.io.*;

import java.util.StringTokenizer;
/**
 *
 * @author  caglar
 */
public class Coor3D {

    private float x = 0;

    private float y = 0;

    private float z = 0;

    /** Creates a new instance of Coor3D */
    private Coor3D(float x, float y, float z) {
        this.x = x;
        this.y = y;
        this.z = z;
    }

    public static Coor3D create(String line){
        StringTokenizer tokenizer = new StringTokenizer(line);
        return new Coor3D(Float.parseFloat(tokenizer.nextToken()),   //x
                          Float.parseFloat(tokenizer.nextToken()), //y
                          Float.parseFloat(tokenizer.nextToken())  //z
                        );
    }

    public void write(FileOutputStream ostream)throws IOException{
        /*int floatBytes = Float.floatToIntBits(this.x);
        long sign = ((floatBytes + 4294967296L) & 0x80000000) >> 31;
        int exp = (floatBytes & 0x7f800000)>>23;
        int sig = floatBytes & 0x007fffff;
        System.out.println(sign);
        System.out.println(exp);
        System.out.println(sig);
        System.exit(0);
        System.out.println("" + (int)this.x + " " + (int)this.y + " " + (int)this.z);

        writer.write((int)this.x & 0xff);
        writer.write(((int)this.x & 0xff00) >> 8);
        writer.write(((int)this.x & 0xff0000) >> 16);
        writer.write(((int)this.x & 0xff000000) >> 24);

        writer.write((int)this.y & 0xff);
        writer.write(((int)this.y & 0xff00) >> 8);
        writer.write(((int)this.y & 0xff0000) >> 16);
        writer.write(((int)this.y & 0xff000000) >> 24);
```

```
writer.write((int)this.z & 0xff);
writer.write(((int)this.z & 0xff00) >> 8);
writer.write(((int)this.z & 0xff0000) >> 16);
writer.write(((int)this.z & 0xff000000) >> 24);

writer.flush();*/
int floatBytes = Float.floatToIntBits(this.x);
/*System.out.println("" + (floatBytes & 0xff));
System.out.println("" + ((floatBytes & 0xff00) >> 8));
System.out.println("" + ((floatBytes & 0xff0000) >> 16));
System.out.println("" + ((floatBytes & 0xff000000) >> 24));*/

int a = floatBytes & 0xff;
if(a < 0) a+= 256;
ostream.write(a);

a = (floatBytes & 0xff00) >> 8;
if(a < 0) a+= 256;
ostream.write(a);

a = (floatBytes & 0xff0000) >> 16;
if(a < 0) a+= 256;
ostream.write(a);

a = (floatBytes & 0xff000000) >> 24;
if(a < 0) a+= 256;
ostream.write(a);

floatBytes = Float.floatToIntBits(this.y);
a = floatBytes & 0xff;
if(a < 0) a+= 256;
ostream.write(a);

a = (floatBytes & 0xff00) >> 8;
if(a < 0) a+= 256;
ostream.write(a);

a = (floatBytes & 0xff0000) >> 16;
if(a < 0) a+= 256;
ostream.write(a);

a = (floatBytes & 0xff000000) >> 24;
if(a < 0) a+= 256;
ostream.write(a);

floatBytes = Float.floatToIntBits(this.z);
//System.out.println(this.z + "      " + Float.intBitsToFloat(floatBytes));
//System.exit(0);
a = floatBytes & 0xff;
if(a < 0) a+= 256;
int a1 = a;
ostream.write(a);

a = (floatBytes & 0xff00) >> 8;
```

```
        if(a < 0) a+= 256;
        int a2 = a;
        ostream.write(a);

        a = (floatBytes & 0xff0000) >> 16;
        if(a < 0) a+= 256;
        int a3 = a;
        ostream.write(a);

        a = (floatBytes & 0xff000000) >> 24;
        if(a < 0) a+= 256;
        int a4 = a;
        ostream.write(a);

        int b = (a4<<24) | (a3<<16) | (a2<<8) | (a1);
        //System.out.println(this.z + "      " + Float.intBitsToFloat(b) + "      " + a1 + " " + a2
+ " " + a3 + " " + a4);
        //System.out.println((char)0x3f);
        //System.exit(0);
    }

    public String toString(){
        return new String("" + x + " " + y + " " + z);
    }

}
```

APPENDIX B

ORIGINAL PLOTS OF KISS-GAIT & VCM

B.1 EXPERIMENT PERFORMED IN ANKARA UNIVERSITY-VICON SYSTEM

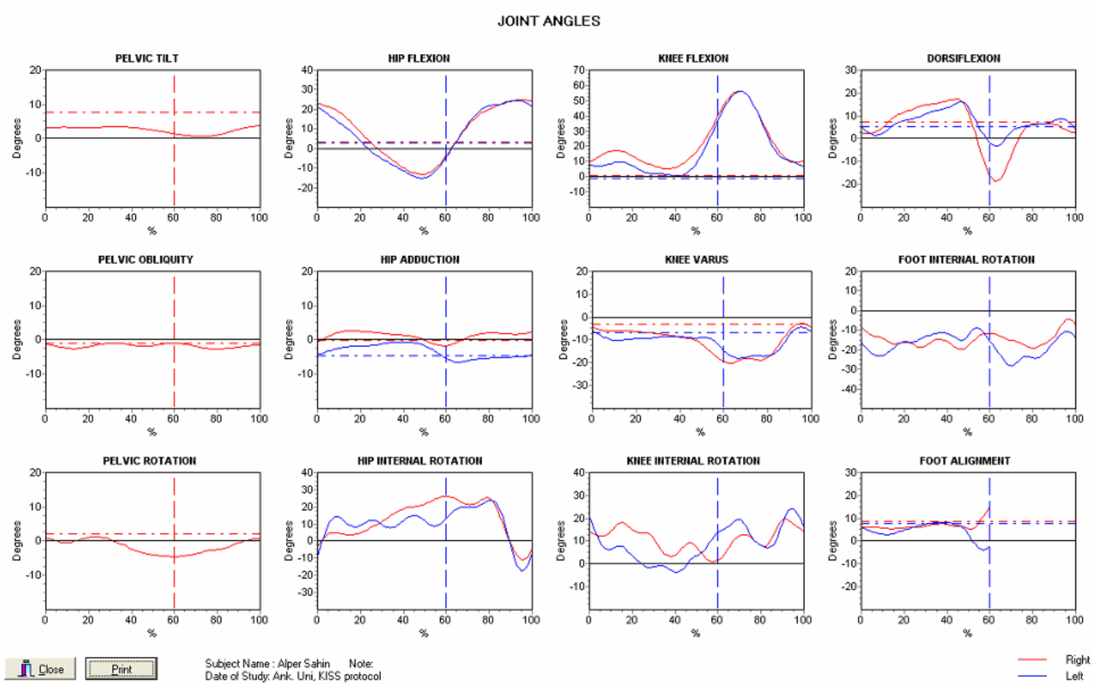

Figure B.1 Original Output Plot of Kiss-GAIT

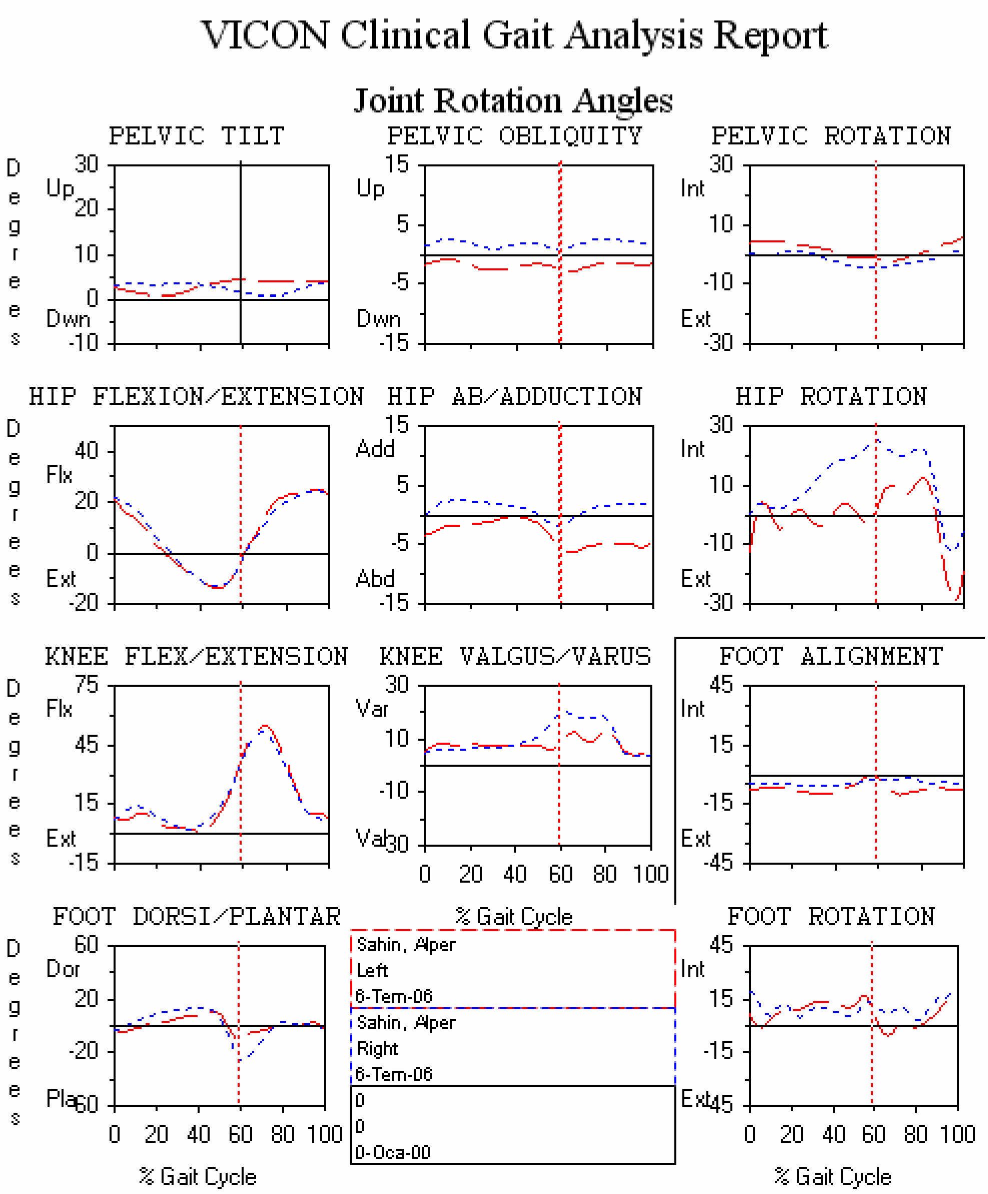

Figure B.2 Original Output Plot of VCM

B.2 EXPERIMENT PERFORMED IN METU-KISS SYSTEM

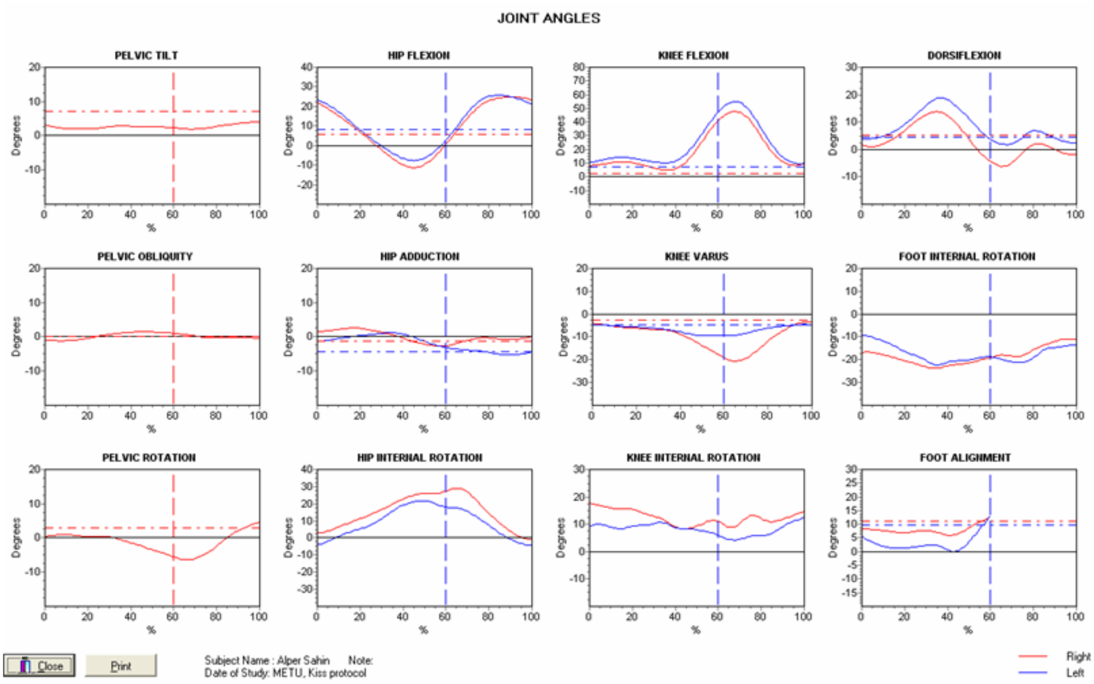

Figure B.3 Original Output Plot of Kiss-GAIT

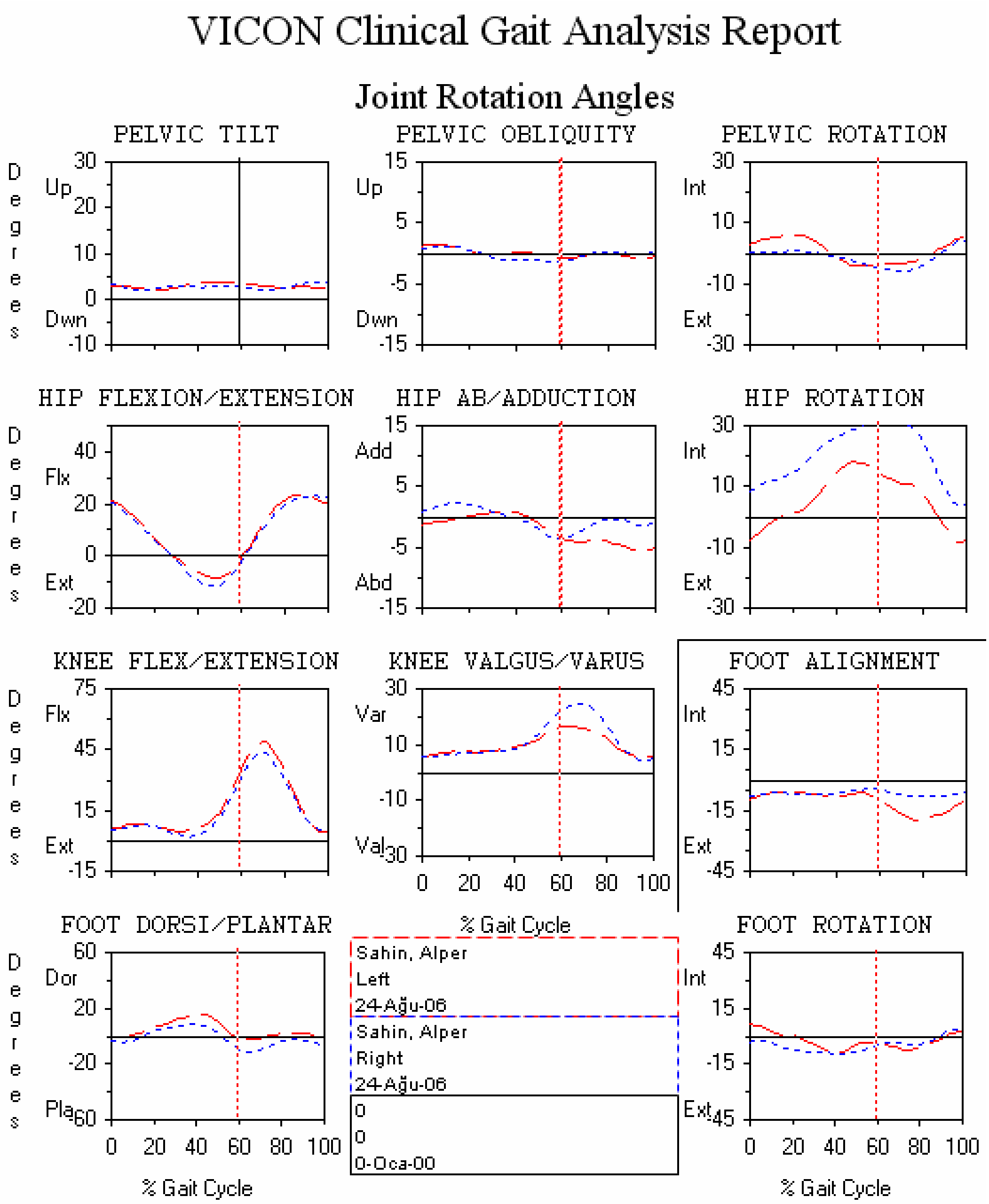

Figure B.4 Original Output Plot of VCM

B.3 Comparison of Kiss-GAIT and VCM Protocols

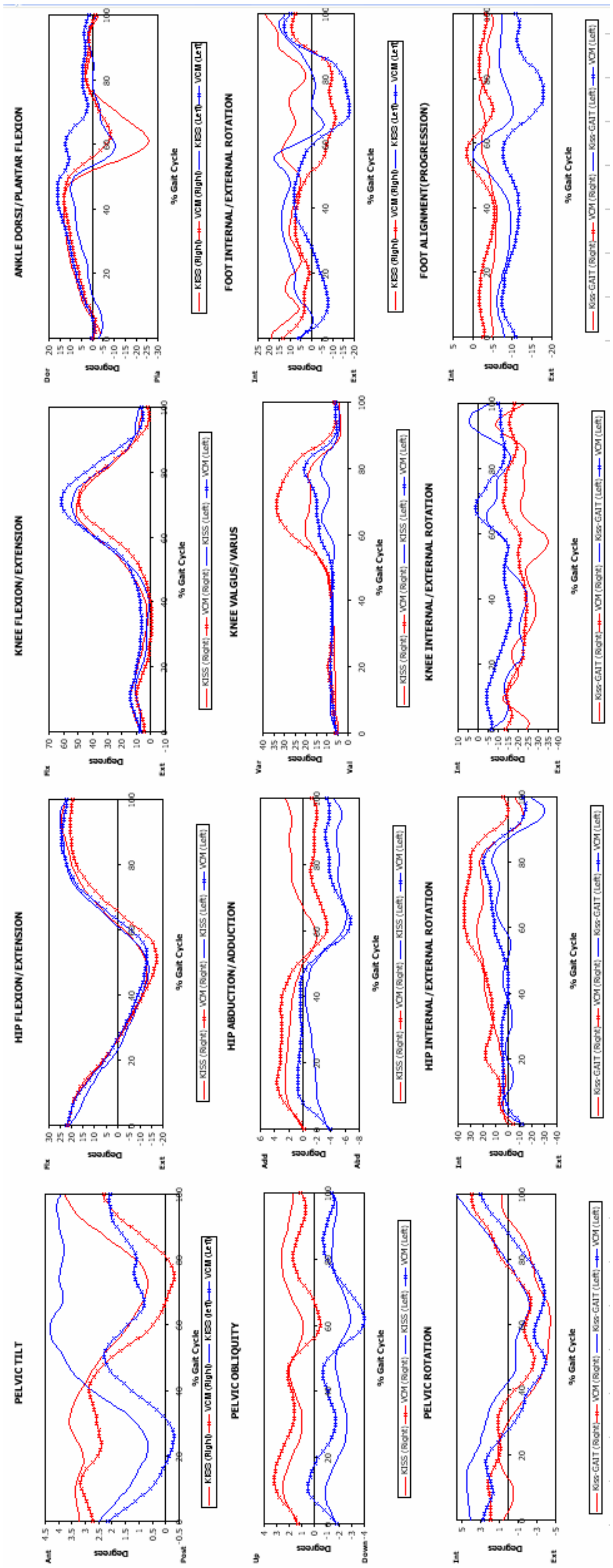

Figure B.5 Comparison of Kiss-GAIT and VCM Protocols analyzed in VCM

GLOSSARY

The following list of terms only describes the biomechanical terms that are used often in this thesis.

Abduction	Movement of a limb away from the midline of the body in the coronal plane.
Active marker	Marker that emit a signal.
Adduction	Movement of a limb towards the midline of the body in the coronal plane.
Anterior	Toward the front of the body.
ASIS	Acronym for Anterior Superior Iliac Spine; it refers to the anterior extremity of the iliac crest of the pelvis.
Cadence	Number of steps taken in a given time, usually a minute.
Calcaneus	The quadrangular bone at the back of the tarsus; also called heel bone.
CCD	Acronym for Charge Coupled Device; it refers to an image sensor consisting of a grid of pixels made up of capacitors sensitive to light.
Coronal (Frontal) Plane	Vertical plane that passes through the midline and divides the body into anterior and posterior portions.

Distal	Refers to the extremities and means away from the trunk.
Dorsal	Toward, on, in, or near the back or upper surface of an organ; e.g. superior portion of the foot.
Dorsiflexion	Bending the ankle so the foot points upward.
Epicondyle	A rounded projection at the end of a bone.
Eversion	(Outward) rotation of the sole of the foot away from the median plane.
Extension	Straightening movement that increases the angle between body parts.
External (Lateral) Rotation	Twisting the extremity outward along its longitudinal axis in the transverse plane.
Femur	Single bone in the thigh located between the hip and knee joint.
Flexion	Movement that decreases the angle between two parts.
Gait	Manner or style of walking, rather than walking process itself.
Gait analysis	The study of human movement for medical purposes. Optical measurement systems can record and analyze such data to generate kinematic and kinetic data.
Gait cycle	Time interval between two successive occurrences of one of the repetitive events of walking.
Greater trochanter	A strong process overhanging the root of the neck of the femur.

Heel Strike	Event in the gait cycle when first contact is made between the foot and the ground; indicates the transition from the swing phase to the stance phase.
Inferior	Away from the head; lower down the body.
Inter-ASIS distance	The length of measure between the left ASIS and right ASIS.
Internal (Medial) Rotation	Twisting the extremity inward along its longitudinal axis in the transverse plane.
Inversion	(Inward) rotation of the sole of the foot towards the median plane.
Lateral	Away from the midline of the trunk.
Malleolus (pl. Malleoli)	A rounded bony prominence on either side of the ankle joint.
Marker	Active or passive object (sphere, hemisphere or disk) attached to specific bony landmarks used to designate segment and joint position in motion capture.
Medial	Toward the midline of the trunk.
Metatarsus	Five long bones of the foot which are numbered from the medial side.
Passive marker	Marker that reflect visible or infrared light.
Pelvis	Bony structure located at the base of the spine; consists of two hip bones, the sacrum and the coccyx.
Plantar	Inferior portion of the foot.
Plantar Flexion	Bending the ankle so the foot points downward.
Posterior	Toward the back of the body.

Proximal	Refers to the extremities and means closer to the trunk.
Sacrum	The large, triangular bone at the base of the spine and at the upper and back part of the pelvic cavity, where it is inserted like a wedge between the two hip bones.
Sagittal Plane	Vertical plane that passes through the midline and divides body into (equal) right and left portions.
Shank	The part of the human leg between the knee and ankle.
Stance	Period in which the foot is in contact with the floor.
Step	Interval between two successive heel strikes for opposite feet.
Stride	Interval between two successive heel strikes of the same foot.
Superior	Toward the head; higher up the body.
Swing	Period during which the foot is not contact with the floor.
Thigh	The part of the human leg between the hip and the knee.
Tibia	The large medial bone of the lower leg.
Toe off	Event in the gait cycle when the foot (generally the toe) leaves the ground; indicates the transition from the stance phase to the swing phase.

Transverse Plane	Horizontal plane that divides the body into superior and inferior portions. Transverse plane is perpendicular to the sagittal and frontal planes.
Valgus	Lateral angulation of the distal segment of a joint.
Varus	Medial angulation of the distal segment of a joint.