IN VIVO VERIFICATION OF DIFFERENT HIP JOINT CENTER ESTIMATION METHODS IN GAIT ANALYSIS FOR HEALTHY SUBJECTS

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ABSTRACT

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Hip joint is one of the most stable joints in human body. It has intrinsic stability provided by its relatively rigid ball and socket configuration. The hip joint also has a wide range of motion, which allows normal locomotion and daily activities. Location of hip joint center (HJC) is an important parameter in gait analysis, biomechanical and clinical research laboratories to calculate human lower extremity kinematics and kinetics.

There exists different methods to determine HJC. Although invasive methods like radiography, computed tomography, magnetic resonance imaging (MRI) and the like may be used to determine the location of HJC, in gait analysis laboratories, non-invasive functional and/or predictive methods are generally found to be more advantageous. METU gait analysis system, utilizes one of the predictive methods, the Davis method (1991) to determine hip joint center location. Kafalı (2007) adopted two functional methods of hip joint center estimation to the system and evaluated the results with respect to Davis method.

This thesis aims to experimentally verify different HJC estimation methods with those obtained from MRI in healthy subjects for the purpose of demonstrating and validating the contribution of MRI procedure in METU gait analysis system. Also combination of Bell's (1990) second method in posterior (x) direction, Davis (1991) method in distal (y) direction and Bell's (1990) second method in medial (z) direction was analyzed and the results were criticized for the accuracy.

Keywords: Gait Analysis, Hip Joint Center, Functional Method, Predective Method

ÖZ

YÜRÜME ANALİZİNDE DEĞİŞİK KALÇA MERKEZİ KESTİRİM YÖNTEMLERİNİN SAĞLIKLI DENEKLER İÇİN YERİNDE-CANLI BELİRLENMESİ

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Kalça eklemi insan vücudunun en kararlı eklemlerden biridir. Onun bu kararlılığı görece sabit küresel mafsal yapısı tarafından sağlanır. Kalça eklemi aynı zamanda normal hareket ve günlük aktiviteleri sağlayan geniş bir hareket aralığına sahiptir. İnsanın alt ekstremitesinin kinematik ve kinetik verilerinin hesaplanmasında kullanılan, kalça eklem merkezi (KEM) konumu, yürüyüş analizi, biyomekanik ve klinik araştırma laboratuvarları için önemli bir parametredir.

KEMnin konumunun saptanması için çeşitli yöntemler bulunmaktadır. Radyografi, bilgisayarlı tomografi, manyetik rezonans ile görüntüleme ve benzeri girişimsel yöntemler KEM konumunu belirlemek için kullanılabilse de, yürüme analizi laboratuvarlarında, fonksiyonel ve kestirimsel yöntemler tercih edilmektedir. ODTÜ yürüme analizi sistemi, KEM konumunu belirlemek için Davis (1991) yöntemini kullanmaktadır. Kafalı (2007) sisteme iki fonksiyonel yöntem daha eklemiştir ve Davis yöntemine göre sonuçları değerlendirmiştir.

Bu tezin amacı, farklı KEM tahmin yöntemlerini sağlıklı deneklerden elde edilen manyetik rezonans görüntüleri ile deneysel olarak değerlendirmek ve ODTÜ yürüme analizi sisteminde KEM konumunu belirlemek üzere, manyetik rezonans yöntemin katkısını göstermek ve doğrulamaktır. Ayrıca posterior (x) yönde Bell'in (1990) ikinci yöntemini, distal (y) yönde, Davis (1991) yöntemini ve medial (z) yönde Bell'in (1990) ikinci yönteminin kombinasyonu analiz edildi ve elde edilen sonuçlar tartışıldı.

Anahtar Kelimeler: Yürüyüş Analizi, Kalça Eklem Merkezi, Fonksiyonel yöntem, kestirimsel yöntem

To my family

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

1.1.1 BIOMECHANICS

Mechanics is a field of science which mainly focuses on the behavior and analysis of objects when subjected to force or displacement. Biomechanics can be assumed as a sub-branch of mechanics. Biomechanics is an approach to the biological systems (generally human and animals) with mechanical point of view.

Biomedical engineering is one of the wide fields of engineering which involves application of some engineering sciences, such as mechanical and electrical. Biomechanics can be applied in system-level device development and implementation, with obvious effect on athletic performance, work environment interaction, clinical rehabilitation, orthotics, prosthetics, and orthopedic surgery (Peterson and Bronzino 2008). This is why biomechanical engineering can only be thoroughly described through a multidisciplinary approach.

1.1.2 DESCRIPTION OF THE LOCOMOTION AND THE GAIT ANALYSIS

Cappozzo in 1984 described walking as the body's natural and the most convenient means of transportation (generally for short distances) from one location to another employing interplay of internal and external forces. Functional adaptability of human lower extremities allows human being to simply accommodate stairs, doorways, changing surfaces, and obstacles in the path of progression. Because of its complexity locomotion can only be completely described through an interdisciplinary point of view, that is to say that biomechanics has the greatest responsibility for establishing the relevant scientific knowledge. Cappozzo (1984) said that ‘the quantitative description of all mechanical aspects of walking is commonly referred to as gait analysis’.

Studies about human walking have a wide range of applications such as medicine, ergonomics, sports science and space technology. Research on mechanical characteristics of the gait requires application of multibody dynamics (Winter, 1979; Berme and Cappozzo, 1990; Vaughan, 1992; Allard *et al.*, 1995). Gait analysis, besides dealing with the mechanical aspects of walking and running, is an assistive tool for medical doctors in diagnosis, treatment planning, and treatment evaluation.

In the field of patient care, understanding of normal locomotion may be assumed to be as bedrock to the knowledge of pathological gait. The prosthetists and orthotists who want to improve the performance of pathological gait deficits patients shall be familiar with joint motion, ground-reaction forces and muscular activity of normal subjects. The kinetic and kinematic data provide the base of supporting knowledge to improve the performance of pathological gait deficits patients (Ayyappa, 1997).

1.1.3 NORMAL GAIT

In order to understand pathologic gait, normal gait has to be defined. Whittle (2007) pointed out that two important cases must be kept in mind when normal gait is going to be defined. Firstly, an appropriate 'normal' standard needs to be presented for the subject who is being studied because the term 'normal' is used for both female and male, a wide range of ages and also wider range of body geometry extremes. The second case is that even though a patient's walking is different from the normal walking in some way, it does not mean that some treatment should be done to make it turn to normal walking.

Normal human walking and running can be defined as 'a method of locomotion involving the alternative use of the two legs'. In order to exclude running from walking, one must say 'during walking at least one foot must be in contact with the ground'. Unfortunately, this definition exempts some forms of pathological gait which are generally regarded as being forms of walking so it is probably both unreasonable and pointless to attempt a definition of walking which will apply to all cases (Whittle, 2007). In normal human gait, the kinematic and kinetic properties of lower extremities in the left and right are symmetric. One of the important characteristics of normal gait is the optimization of energy (minimum energy consumption) which means that any abnormality increases the referred minimum energy consumption during gait.

1.1.4 APPLICATIONS OF GAIT ANALYSIS

The applications of gait analysis are conveniently divided into two main categories: clinical gait assessment and gait research. The aim of clinical gait assessment is helping individual patients directly (concentrating on methods of treatment or surgery), whereas gait research has the aim of improving our understanding of gait (such as research on methods and instruments of gait data measurement and data collection, the advancement of knowledge in locomotion and data analysis, human body performance and ergonomy). There is obviously some overlap, in that many people performing clinical gait assessment use it as the basis for research studies. Davis (1988) stated that there are considerable differences between the technical requirements for clinical gait assessment and those for gait research. In gait research, it may be acceptable to spend a whole day preparing the individual, performing the measurements, collecting and data processing, whereas in the clinical gait experiments, subjects can be tired fast and the experiments are usually required to be performed as quick as possible. The requirements for accuracy, generally, in the clinical setting are not (and also not required) as good as they are in the research laboratory. Another important point is that there is no value in using complicated and expensive measurement systems in clinical gait analysis, unless it provides information which is useful and which cannot be obtained in an easier way.

1.1.5 HIP JOINT

Human joints, limbs, and muscles represent a collective of individual pieces which all work together to move the body, manipulate objects, and propel the body through 3-D space.

The human hip joint is well constructed for its intended use: standing and walking. It is one of the largest and most stable joints in the body. Hip joint is a spherical type joint connecting the head of the femur and acetabulum of the pelvis. The hip joint is weight bearing joint and also has a wide range of mobility, which allows normal locomotion (walking and running) in the performance of daily activities.

1.1.6 ANATOMICAL CONSIDERATIONS OF HIP JOINT

Hip joint is composed of the head of the femur which forms two thirds of a sphere and the acetabulum of the pelvis which is a spherical socket (Figure 1). This articulation has a loose joint capsule and is surrounded by large and strong muscles. The stable construction of this joint allows of the wide range of motion during daily activities. In a normal hip joint, the center of the femoral head coincides exactly with the center of the acetabulum. The rounded part of the femoral head is spheroidal rather than spherical because the uppermost part is flattened slightly. This causes the load to be distributed in a ring-like pattern around the superior pole (Peterson and Bronzino, 2008).

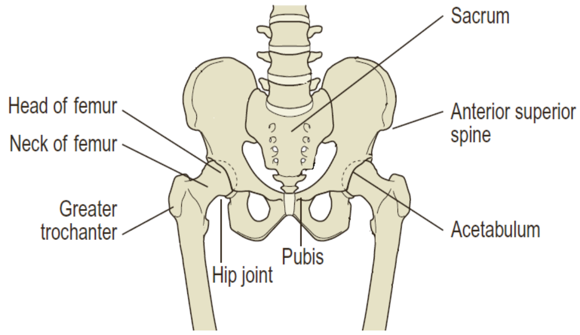


Figure 1 Hip joint (adapted from Whittle, 2007).

1.2 PROBLEM DEFINITION AND IMPORTANCE OF THE ESTIMATION OF THE HIP JOINT CENTER (HJC) LOCATION FOR GAIT ANALYSIS

Motion analysis of the lower extremities of living subjects usually requires determination of the location of the hip joint center (Piazza, 2004). Estimation of joint centers is required for many types of walking studies for kinematic and kinetic elaboration (Frigo, 1998). Inaccuracies in estimation of hip joint center are shown to propagate errors in kinematic and kinetic calculations of lower extremities (Della Croce et al., 2005).

Calculation of gait parameters from stereophotogrammetric data requires utilization of classical mechanics together with biomechanical models which represents human body as a mechanical system. Obviously, procedures employed in these calculations are directly associated with the experimental protocol. Adaptation of various joint center estimation methods to Middle East Technical University (METU) gait analysis system Kiss (Kinematic Support System in English, *Kas İskelet Sistemi* in Turkish) and investigation of the effects of joint center location on kinematic results undoubtedly require modifications to be introduced to the experimental protocol, and consequently, to the calculation methodology. In the current gait analysis protocol, kinematic and kinetic calculations are performed by in-house Kiss-GAIT software which was originally developed in Delphi® (Delphi Corporation, Troy, MI, USA) by Güler (1998) then transferred to Matlab® environment by Kafalı (2007) and Erer (2008).

In kinematic calculations of gait parameters (such as joint angles), determination of hip joint center is necessary and in METU gait analysis system the method presented by Davis et al. (1991) has been used to construct required segment coordinate systems. This method is very straightforward and easy to use. However, in this method the determinations of the position of anatomical landmarks depend on the experience of the conductor and anatomical properties of the specimens (any anatomical variations of the specific subject will cause errors). One of the major sources of error propagation in kinematic and kinetic calculations is due to misplacement of hip joint center (Kafalı, 2007).

1.3 METHODS OF ESTIMATING HJC LOCATION

Investigators have tried to locate HJC in living subjects (known as *in vivo* estimation of HJC) by several different methods. Two major methods of HJC estimation which are presented in the literature are invasive and noninvasive. Each method can also be subdivided into two branches as below:

Invasive methods:

1- X-rays and computed tomography (CT)

2- Three-dimensional ultrasound imaging (USI) and magnetic resonance imaging (MRI)

Non-invasive methods:

1- Functional methods

2- Anthropometric methods

From these two non-invasive methods, anthropometric methods utilize location of external landmarks and functional methods utilize relative motion between the segments for hip joint center determination.

1.4 MOTIVATION AND SCOPE

Gait analysis systems measure the motion of the body segments and ground reaction forces. Measured data is used for creating mathematical models and these models are used to calculate joint angles, moments, power and other mechanical properties of joints and limbs. Applied technology for kinematic analysis of body segments and joints is the motion capture system. For analysis of the lower extremity motions, estimation of the location of the hip joint center is necessary. Because it is subject specific and due to its importance in clinical studies and in gait research, many scientists and physicians are trying to locate the hip joint center as precisely as possible. In gait analysis, HJC is used in calculating joint kinematic and kinetic data in healthy and pathological subjects. The goal is to predict the hip joint center optimally to achieve more precise and reliable kinematic and kinetic data of human lower extremity joints. Several ways of in vivo determination of hip joint center are presented in the literature until now. In gait analysis laboratories, HJC is tried to be located as close as possible to the exact location by functional and/or predictive (anthropometric) methods.

METU gait analysis system has been operating since 1999 and many studies in gait analysis have been done including estimation of hip joint center location using various techniques. The sensitivity of METU gait analysis protocol to HJC estimation has been assessed by Kafalı (2007). However, the golden standard, determination of HJC by invasive methods and comparison of other methods with this golden standard was left as a future work. This thesis aims to obtain HJC through magnetic resonance imaging (MRI) method and three-dimensional reconstruction of the image slices, fitting a sphere to the head of the femur. The results of this golden standard will be compared with other non-invasive methods. The advantages of each method, together with their accuracy in kinematic and kinetic calculations will be compared.

1.5 OUTLINE OF THE THESIS

Chapter 2 presents a survey of literature regarding the estimation methods of HJC including previous studies performed in METU gait analysis protocol.

Chapter 3 presents detailed explanation of the procedure and the methodology followed in this study. One of the novel contributions of this study is proposing a method to coincide the MRI coordinate system with pelvic coordinates.

Chapter 4 presents results, evaluation and discussions of different hip joint center estimation methods analyzed in this thesis.

Chapter 5 compares the results of a hybrid method with MRI and Davis methods. The results of the proposed discussed and finally conclusions and future works presented.

CHAPTER 2
LITERATURE SURVEY

2.1 INTRODUCTION

Error existence in locating joint centers directly influences kinematic and kinetic properties of the joint by affecting position and orientation of constructed segmental anatomical reference frames. Therefore, determination of joint centers with high accuracy becomes a critical issue to obtain reliable results in clinical and research oriented gait studies.

The literature survey chapter is divided into three main parts. In the first part, need for the hip joint center estimation are expressed by referring to published materials and their results which show how mislocation of HJC affects kinematic and kinetic data in gait analysis. In the second part, different methods of hip joint center estimation are presented and classified into two groups, each group explained briefly. According to the classification of the methods in the second part, the third part, available methods in literature, is divided into three subparts, and in each subpart, previous published material are investigated and criticized by referring to their results, advantages and disadvantages.

2.2 NEED FOR DETERMINING HJC

Accurate estimation of the HJC is paramount for application of inverse dynamic models in clinical and laboratory movement analysis (McGibbon, 1997).

2.2.1 STUDIES ON THE EFFECT OF HJC MISLOCATION:

Crowninshield et al. (1977), Andriacchi and Strickland (1983), and Kirkwood et al. (1999) studied the effects of HJC mislocation on hip kinetics. Cappozzo (1986) has shown how the inaccuracies in hip, knee and ankle joint center estimation propagate error to the kinetics of the former joints. Holden and Stanhope (1998) worked on the same problem but referenced to joint center and kinetics of the knee only.

Effects of hip joint center mislocation on gait studies results were analyzed by Stagni et al. in 2000 on five able-bodied subjects. In their study, the nominal position of the HJC was calculated as the position of the pivot point of a 3D movement of the thigh relative to the pelvis. Angles and moments of the lower extremity joints were then re-calculated after having added to HJC co-ordinates errors in the range of ±30 mm in three anatomical directions (in pelvis anatomical reference frame).

The nominal location of the HJC in the pelvic anatomical frame was determined as the center of the optimal spherical surface that fitted (in a least squares sense) the trajectory of the centroid of the thigh markers while the subject performed the hip flexion/extension and an abduction/adduction movement. Both hip and knee joint angles and moments were directly affected by HJC mislocation.

According to the results, the largest propagation of error belongs to hip moments. A 30 mm HJC anterior mislocation reduces flexion/extension component about 22%. The second largest affected quantity was the hip abduction/adduction moment in which: A 30 mm lateral HJC mislocation reduces abduction/adduction moment about 15%. A 30 mm posterior HJC mislocation produced a delay of the flexion-to-extension timing in the order of 25% of the stride duration.

2.3 CLASSIFICATION OF HJC ESTIMATION METHODS

Many studies have performed regarding estimation of HJC location on living subjects by a variety of methods. Two major sub-classes are invasive and non-invasive:

2.3.1 INVASIVE METHODS

Inaccessible location of HJC (it is deep inside the soft tissues and is in the center of femur head) prevents its exact determination in living subjects. For this reason, some investigators applied invasive methods to determine exact location of HJC.

I- Radiography and CT are used by some researchers (Crowninshield et al., 1978; Ellis et al., 1979; Johnston et al., 1979) to determine the exact position of the HJC. Most studies consists of radiography to evaluate the error between exact and estimation methods.

II- Three-dimensional ultrasound imaging (Fenster et al., 2001) or 3-D freehand ultrasound (3-DUS) is an inexpensive alternative which is becoming more widely available (Peters et al., 2010). MRI is another method which is applied by some other researchers (Sangeux 2011).

Although HJC could be precisely located by orthogonal x-rays, MRI and three-dimensional ultrasound imaging, there are significant difficulties (such as being time consuming and expensive, exposition to X-rays) in taking, developing, and interpreting. Also, subjects (especially children and adults of child-bearing age) should not be exposed to ionizing radiation (x-rays) (Bell et al., 1989).

2.3.2 NON-INVASIVE METHODS

Researchers were trying to replace invasive methods by simple, cheaper and more importantly non-invasive methods which are reliable and applicable in gait analysis laboratories. Two non-invasive methods which are used in literature for hip joint center prediction from surface marker coordinates (using external landmarks) with its advantages and disadvantages are discussed.

I. THE FUNCTIONAL METHODS

Due to the geometry of the femoral head, hip joint is modeled as a spherical joint. In this approach, the movement of a marker on the thigh is fit to a sphere whose center coincides with the hip joint center. Using this idealization, functional methods utilize relative motion between thigh and pelvis segments to determine hip joint center locations. The functional methods generally apply sphere-fitting and least square algorithms. For defining the coordinates of the points in space stereometry has been used since about 1947. Stereometry uses three-dimensional (3-D) reconstruction of the instantaneous position of a moving point in a laboratory coordinate system. There are some parameters which affect the accuracy of determining HJC by functional methods such as:

a. The range of motion in flexion–extension, abduction–adduction, or in other types of daily movements (such as walking and sit to stand).

b. The specific algorithm used to fit a sphere to the data.

c. The methods of placing markers on the thigh (marker cluster design).

d. The type of motion used to generate points, either walking or a standing leg motion (SLM) trial.

e. Motion of markers on the soft tissue during movements (soft tissue artifact).

f. Duration of movement.

II. THE PREDICTIVE METHODS

These methods estimate the hip joint center with respect to position of anatomical landmarks. These methods utilize anthropometric measurements taken from subject's body segments together with regression equations obtained from a number of either radiologic or cadaveric studies, to estimate hip joint centers coordinates.

This method is very straightforward and easy to use. The results of the predictive methods depend on the position of anatomical landmarks and measurement which varies upon expert opinion. The extracted equations can also be affected by the number of contributed subjects to the study, sex and age of the subject. It should be noted that these methods are applicable in HJC estimation of healthy subjects not pathologic or other anatomically variant subjects.

2.4 NON-INVASIVE METHODS IN THE LITERATURE

There are many studies on non-invasive methods of HJC estimation which are presented and discussed in the following sections.

2.4.1 FUNCTIONAL METHODS

1- Cappozzo (1984) for the first time, represented a functional method of HJC estimation based on the assumptions that (1) the thigh is a rigid body, and (2) the HJC is the center of a sphere represented by the 3-D rotation of a point on that body, but no error estimates of the method presented were reported. In his method, the subject performed a movement of abduction-adduction of the thigh followed by a flexion-extension. Using the reconstructed 3-D trajectories of the thigh markers it was possible, through a least-squares method, to estimate the location of the center of rotation of the movements on the hip.

2- In 1990 Bell et al. evaluated the precision of Cappozzo's rotational method and concluded that related rotational method could only estimate the HJC within 3.79 cm of the exact location (determined by radiography) and they referred that these results cannot be assumed as an accurate method (Table 1). In their experiment rotational method was reproducible from run to run for each subject to within about 2 cm. Figure 2 presents the coordinate system used by Bell et al. (1990).

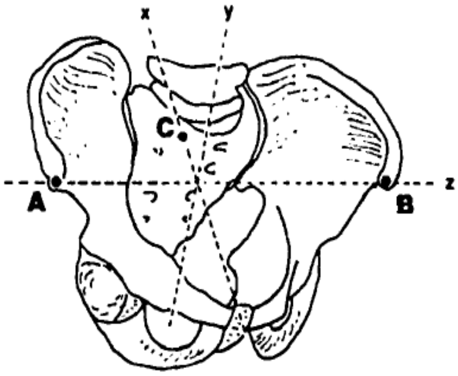


Figure 2 Pelvic marker reference frame used by Bell et al, (1990), right ASIS, point A, left ASIS, point B, and mid-PSIS point C.

Table 1 Hip joint center estimation error using rotational method (Bell et al, 1990) with respect to pelvic marker reference frame.

-	Δ_X, cm	Δ_Y, cm	Δ_Z, cm	Total error (cm)
Average of all runs	2.05	2.12	1.45	3.79

The error originates from the fact that firstly the method requires as many points as possible in three directions; secondly the human leg rotation is confined (according to Nordin and Frankel, (2001), external rotation ranges from 0 to 90° and internal rotation from 0 to 70°) especially in elderly and pathologic population and thirdly as they pointed out this system could not construct correct sphere.

3- A functional method was presented by Halvorsen et al. (1999) for estimating the parameters of two different joint models: a rotational joint with a fixed axis of rotation, also known as a hinge joint, and a ball and socket joint model, referred to as a spherical joint. For the spherical joint, three non-parallel and non-planar displacements are necessary and sufficient information to find the center of rotation (CoR). In this case the point paths lay on the surface of a sphere with radius equal to the distance to the CoR.

Two different simulation results (linked rigid bodies utilized as models of extremities) indicated that methods that utilize the rigid body assumption are superior to the proposed method (when measurement noise is present). However, when the large skin artifact movement exits, simulation results showed that the proposed method is more reliable than the other methods in same situation.

4- Piazza et al. (2001) studied the motions of a mechanical linkage (Figure 3). The linkage has two independent segments representing the pelvis and left thigh. Clusters of four reflective markers were rigidly attached to each segment. A cardboard tube placed beneath the ball joint of the linkage was used to limit range of hip motion (Figure 3-right). Their purposes were, evaluating the potential accuracy of the functional method and analyzing the dependence of its precision in various movements and magnitude of hip motion. By rigid attachment of markers to each segment in the mechanical linkage, the errors due to skin movement are eliminated.

The results suggested that the accuracy of the functional method of HJC location is not satisfied when hip joint motion is limited, as has been suggested previously (Bell et al., 1990; Kirkwood et al., 1999; Seidel et al., 1995). The error in HJC location when linkage hip joint motions were limited to 15° was found to be noticeably larger than corresponding trials when the motions were limited to 30°. Also neither increasing the number of movements nor analyzing the motion of a single thigh marker was found to increase error, significantly. Increasing the duration of the motion performed had very little effect on HJC location accuracy.

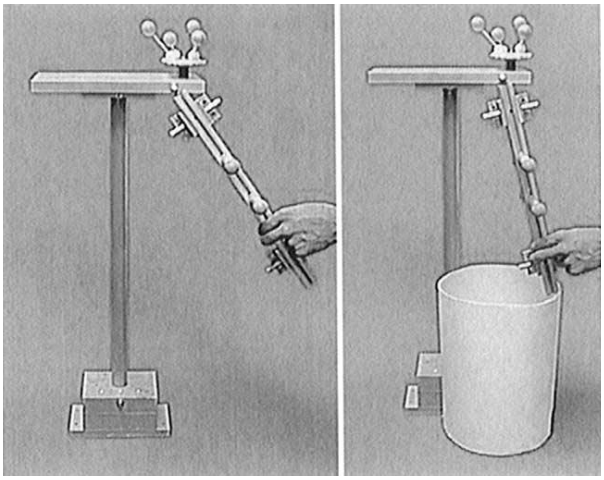


Figure 3 The linkage used in the experiments by Piazza et al. (2001).

Overall, the study by Piazza et al. shows that although not completely satisfactory, the limited range of motion, that is more often in pathologic and elderly subjects, does not prevent determination of the HJC in acceptable range (if the movement is standing leg motion trial), using functional method; and provides guidelines to apply the functional method in human subjects.

5- Piazza et al. (2004) presented a study to clinically validate the accuracy of the functional method they presented in 2001. Young and elderly subjects with limited hip motion (both in magnitude and in direction) were selected. To estimate the location of the HJC, the data were collected during generally studied motions (such as walking, sit-to-stand, stair ascent, stair descent) rather than from an ad hoc trial (which formed, arranged or done for a particular purpose only such as adduction/abduction and rotation) in which varied hip motions are performed.

The idea behind limitation of hip motion is that if accurate locating of the hip joint center is possible using hip motions that are small in magnitude or that are confined to a single plane by using the functional method using common daily motions such as walking. Such an application would eliminate the need for a special trial in which the subject (especially elderly and pathologic subjects) is required to perform (such as circumduction of the hip and perform uncomfortably large abduction–adduction and flexion–extension movements).

The results of the research presents that functional methods would result 26 mm errors in HJC location (in the worst-case) when hip motion is significantly limited (the reduced forms of motion were: limited flexion–extension, limited abduction–adduction, and a combination that limited both sagittal and frontal-plane motion). In the case of data collected from commonly performed motions (stair descent, stair ascent, sit-to-stand and walking) much larger errors (around 70 mm in worst-case) were found in hip joint center location. Overall, the functional method can be used successfully in limited range of motion but requirement for collection of a special motion trial was not solved.

The major limitation of their study is that the exact hip joint center was not determined in the subjects. The presented ‘‘errors’’ in the study shows distances to the hip joint centers that were functionally determined using the full varied hip motion (VHM) trial rather than the distances to known hip joint centers found through the use of radiography or other in vivo imaging techniques which are believed to be more accurate.

6- Hicks et al. (2005) investigated four parameters affecting sphere fit method of HJC estimation using computer simulation and clinical data: 1) the motion range in flexion–extension and abduction–adduction; 2) the specific algorithm (functional method) used to fit a sphere to the data; 3) the method of placing markers on the thigh; and 4) the type of motion used to generate points, either walking or standing leg motion (SLM) trial. Another aim of the study was comparing the precision of the functional method to the mostly applied predictive approaches (methods of Bell and Davis). The location of the HJC resulted from both methods (functional and predictive) were compared to an ultrasound-determined hip center standard, and linear errors and errors along each axis were compared. Results from the computer simulation presented that in functional methods the iterative algorithm shall be applied. Clinical results showed that the functional method with standing leg motion (SLM) trial produced noticeably smaller errors in HJC estimations with respect to the predictive method.

7- Begon et al (2007) presented a study that tests the relation of movement type on HJC estimation accuracy in functional methods. The results of study (Table 2) showed that the nature of movement, the type and the number of cycles have a noticeable effect on the HJC estimation.

Trials with 10 limited cycles of flexion/extension (FE), abduction/adduction (Ab/Ad) and circumduction (Cir.) movements produced the most accurate (average error of 4.0 mm maximum or average error??) estimation of the hip joint center. Accuracy was mainly improved by associating different types of movements. Limited amplitude movements resulted better compared to large motion amplitude.

Table 2 Average errors (and standard deviations) for each test (mm) presented by Begon et al (2007).

Natures of movement	Number of cycles	Types of movements		
		FE/AbAd	Cir.	FE/AbAd/Cir.
Limited	1	7.9 (2.5)	5.0 (1.5)	4.9 (1.6)
	5	6.2 (2.1)	4.8 (1.3)	4.5 (1.5)
	10	5.5 (1.9)	4.5 (1.2)	4.0 (1.3)
Full	1	6.7 (2.3)	5.8 (1.9)	4.7 (1.4)
	5	6.7 (2.1)	5.7 (1.6)	4.6 (1.4)
	10	6.5 (2.1)	5.7 (1.5)	4.6 (1.4)
Explosive	1	6.1 (2.0)	6.7 (2.1)	4.8 (1.6)
	5	5.7 (1.9)	6.5 (2.3)	4.6 (1.7)
	10	5.7 (1.9)	6.5 (2.3)	4.5 (1.6)

8- MacWilliams (2008) compared four functional methods for both rigid and deformable body using a mechanical analog of the lower extremity. Results (Table 3) indicated that while all methods have produced accurate measures under rigid body conditions, there were many differences between methods in deformable conditions. Under deformable conditions, the performance of the method described by Gamage and Lasenby (2002) is better than the other examined methods. Maximum mean errors for this technique were about 1 cm for center of rotation (CoR) in medial direction. Mechanical analog configurations presented by MacWilliams (Figure 4) were tested for two joints in two conditions: Figure 4-A shows rigid body (RB) and (Figure 4-B) shows deformable body (DB) hip CoR testing condition.

Table 3 Summary of all tests results (mean ± S.D.), performed by MacWilliams (2008)

Method		Hip Joint Center Location (mm)		
		Anterior	Medial	Superior
Rigid Body				
	Halvorsen	0.1 ± 2.7	-4.4 ± 6.4	-4.1 ± 2.5
	Gamage	-0.7 ± 0.3	0.5 ± 0.6	-3.4 ± 1.9
	Schwartz	-0.2 ± 0.2	0.5 ± 0.3	-0.9 ± 0.9
	Siston/Spoor	-0.2 ± 0.2	0.5 ± 0.4	-0.9 ± 0.9
Deformable Body				
	Halvorsen	-0.8 ± 10.8	-13.5 ± 16.6	-32.2 ± 44.4
	Gamage	-2.0 ± 5.5	7.4 ± 2.8	3.6 ± 7.8
	Schwartz	7.2 ± 6.9	-0.4 ± 6.6	-25.2 ± 10.3
	Siston/Spoor	6.6 ± 6.8	-0.6 ± 6.1	-24.3 ± 9.9

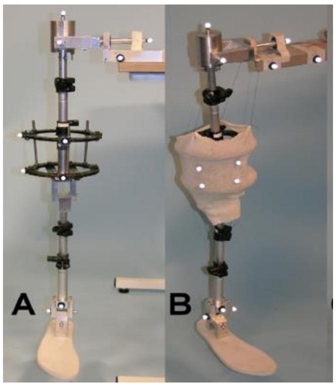


Figure 4 Mechanical analog configurations used by MacWilliams (2008).

9- HJC location was studied by Cereatti et al. (2009) with the aims of calculating the maximum accuracy with which the HJC position can be located using stereophotogrammetry and investigating the effects of hip motion amplitude on this accuracy.

For determining the HJC (from four adult cadavers), a proximal and a distal thigh skin marker cluster (Figure 5) and two analytical methods, the quartic sphere fit (QFS) method and the symmetrical center of rotation estimation (SCoRE) method, were used. According to the authors' results, if photogrammetric error is considered as the only existing error, it can be concluded that the analytical methods performed equally well. In existence of soft tissue artifact (STA) the predicted error (depending on subjects, methods, and skin marker clusters) ranged between 1.4 and 38.5 mm. The largest errors were found in the subjects who showed the largest STA amplitude and the largest thigh diameters.

For the variability associated with marker cluster location, the results show that the HJC estimation errors were dramatically lower when using the distal marker clusters (error range: 1.4–24.7 mm) instead of the proximal marker clusters (error range: 3.1–38.5 mm). This was due to the fact that STA amplitudes of the distal skin markers were significantly lower and also the location of the markers (distal or proximal) affects the results directly. For all subjects, the smallest estimation errors were found when the QSF method was used (error ranged between 1.4 and 31.3 mm and average error, for overall subjects, skin marker clusters and movement repetitions, was 12.1 mm (S.D. 9.4 mm). For the SCoRE method, over the same conditions, error ranged between 6.0 and 38.5 mm, and average error was 21.8 mm (S.D. 8.6 mm).

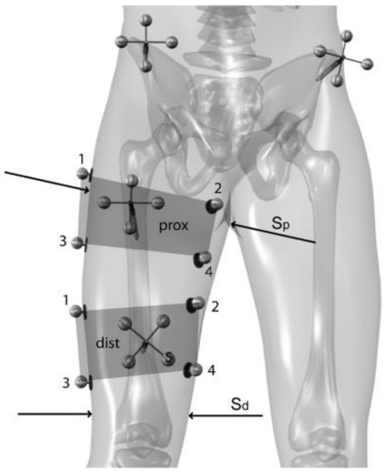


Figure 5 Pin clusters and skin markers configuration (Cereatti et al., 2009).

2.4.2 PREDICTIVE METHOD USING REGRESSION EQUATIONS

1- Some investigators such as Eberhart and Inman (1951), Paul (1965), Pedotti (1977) and Harrington (1976), have estimated the location of HJC by predictive method applying external landmarks (Bell et al. 1990). To decrease the error of predicting HJC location using anthropometric method, some investigators (Andriacchi et al., 1980, 1982; Andriacchi and Strickland, 1983; Tylkowski et al., 1982) used external palpable landmarks. In 1989 Bell et al. evaluated their approach for accuracy and validity in children and adults (all having a normal bony framework) of both sex (Table 4).

Tylkowski et al. examined the anterio-posterior and lateral pelvic x-rays of 200 patients at the Children’s Hospital Medical Center (Boston, USA) Growth Study Clinic. They used five skeletal pelvises to calculate the distance from the ASIS to the hip joint center and estimated that it would be 11% of pelvis width (PW) medial to, 12% of PW distal to, and 21% of PW posterior to the ASIS. Andriacchi et al. (1982) examined the AP pelvic x-rays of 20 patients with no hip pathology. Their results showed that HJC location is in 1.5 to 2 cm distal to the midpoint of the line connecting ASIS and pubic symphysis (Figure 6) in frontal plane.

Table 4 Comparison of the accuracy of the HJC location by prediction method in 2-D and 3-D, using 95% of confidence intervals (Bell, 1989)

	2-D (frontal plane, cm)		3-D (cm)
	Children	Adults	Adults
Tylkowski's approach	1.5	2.7	3.3
Andriacchi's approach	1.1	1.6 (women) 1.8 (men)	-
Combined approach	-	-	2.6

Using Tylkowski's approach, Bell found that 3-D HJC location in adults was 30% of PW to the distal, 14% of PW to the medial, and 22% of PW to the posterior side with respect to the ASIS. Bell estimated HJC location within 3.3 cm of its true location with 95% certainty.

Using Andriacchi's approach, Bell found that HJC was located in the frontal plane distal and lateral to the midpoint of a line between the ASIS and pubic symphysis, varying from 2.2 cm distal and 0.78 cm lateral in females to 4.6 cm distal and 1.7 cm lateral in males.

2- In another evaluation, Bell et al. (1990) explained that none of the examined three methods of HJC estimation (Cappozzo's rotational, Andriacchi's and Tylkowski's methods) seem to be particularly accurate. He mentioned that the rotational method could only estimate the HJC within 3.79 cm of the exact location. Andriacchi's method, with overall generated errors of 3.61 cm (S.D. ±1.2 cm), was a little more accurate than rotational method. This method also is more accurate in AP location (x direction) but relatively inaccurate in predicting the location in frontal (y-z) plane. Tylkowski's method was twice as accurate as either of the other two mentioned methods (within 1.90 cm (S.D. ± 1.2 cm) of the true location), but was less precise in locating the AP location of HJC.

To improve the accuracy of HJC estimation, Bell presented a more precise approach (named as hybrid method). The hybrid method is combination of Tylkowski approach in the frontal plane and the method presented by Andriacchi for AP location. This hybrid method can locate the HJC within 1.07 cm of true location. The obtained results in this study are noticeably similar to the results of their previous study (Bell et al. 1989): HJC location predicted in adults to within 2.6 cm of the exact location with certainty of 95%.

3- A predictive method proposed by Davis et al. (1991) locates hip joint center by the use of regression equations and some anthropometric measurements such as pelvic width, leg length, and marker radius values. The base model for this study was developed at Newington Children's Hospital in 1981 in which the relations and coefficients are obtained from radiographic hip studies of 25 subjects.

4- Seidel et al. (1995) aimed to find relation between HJC location and some selected pelvic geometry (Figure 6) such as pelvic width (PW), pelvic depth (PD) and pelvic height (PH). They studied anatomical anthropometric measurement of 65 adult human cadaveric pelvises and found that HJC location relative to ASIS, optimally located in 14% of PW medially (same with Bell's results in 1989 and 1990 and with mean error of 0.58 cm), 34% of PD posteriorly (mean error of 0.30 cm), and 79% of PH inferiorly (mean error of 0.35 cm), (Table 5). In the study, it was shown that to accurately locate the HJC, not just pelvic width (PW) but also pelvic height (PH) and depth (PD) must be used. In all instances, the error was calculated as the absolute value of the specific estimate value minus the true value.

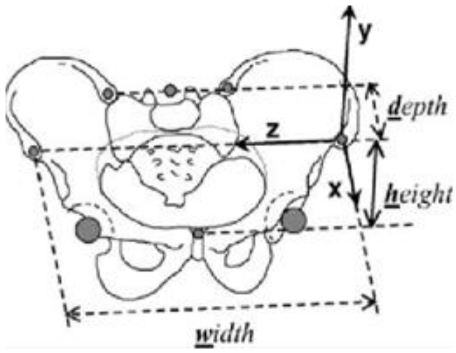


Figure 6 Anatomical landmarks (ASISs, PSISs, sacrum and pubic symphysis as small grey circles, HJC as larger grey circles) and geometrical measurements of pelvis (pelvis width, pelvis depth and pelvis height).

HJC estimation relative to the ASIS as a function of PW alone results in significant deviations from the true HJC location but the estimation as a function of pelvic width, height and depth parameters yields optimized location of HJC relative to true HJC location. The correlation analysis showed that both HJC-x and HJC-y do not vary in a predictable linear relationship with PW, while HJC-z does strongly vary predictably with PW (Table 6).

Seidel et al. (1995) did not find any noticeable differences between male and female in HJC location, also the applicability of their results to HJC estimation in children is unknown. The correlation of randomly selected hips of pooled male and female indicated that errors are expected when locating HJC as a function of PW on any axis except the mediolateral direction (z axis). The correlation (Table 6) suggests that HJC-x and HJC-y do not vary predictably with pelvic width and thus cannot be accurately located as a function of PW.

Table 5 Errors presented by Seidel (1995), in estimating HJC-x (anterior), HJC-y (distal), and HJC-z (medial) resulting from various algorithms (dimensions are in cm).

	Absolute value				
	N	Mean	S.D.	Min.	Max.
Bell (1990) HJC-x 19 % PW	65	1.19	0.51	0.32	2.19
Bell (1989) HJC-x 22 % PW	65	0.58	0.44	0.03	1.51
Seidel (1995) HJC-x 24 % PW	65	0.49	0.34	0.03	1.49
Seidel (1995) HJC-x 34 % PD	65	0.30	0.23	0.00	0.89
Bell (1989, 1990) & Seidel (1994) HJC-y 30 % PW	65	0.75	0.56	0.01	2.26
Seidel (1995) HJC-y 79 %PH	65	0.35	0.28	0.00	1.29
Bell (1989, 1990) & Seidel (1995) HJC-z 14 % PW	65	0.58	0.42	0.00	2.18

Table 6 Descriptive statistics of hip joint center with respect to pelvic measurements (Seidel, 1995).

	Mean	S.D.	Number	Correlation (r)
HJC-x/ PW	24%	3%	65	-0.17
HJC-z/PW	14%	3%	65	0.85
HJC-y/PW	30%	4%	65	0.01
HJC-y/PH	79%	5%	65	0.81
HJC-x/PD	34%	2%	35	0.54

5- Since there was limited relevant anthropometric data available for children (despite for children with cerebral palsy) until 2007, pelvic MRI scans of eight adults, 14 healthy children and 10 children with spastic diplegic cerebral palsy were taken and analyzed by Harrington et al. (2007). The results from three common regression equations (Table 7) for HJC location were compared to those found directly from MRI (LL is leg length and X_{dis} equals to $0.1288\ (LL) - 48.56$). Maximum absolute error of 31 mm was found in adults, 26 mm in children, and 31 mm in the cerebral palsy group. Results from regression analysis and leave-one-out cross-validation techniques on the MRI data suggested that the best parameters for presenting HJC location were: pelvic depth for the antero-posterior (x) direction; pelvic width and leg length for the supero-inferior (y) direction; and pelvic depth and pelvic width for the medio-lateral (z) direction.

Table 7 Prediction equations from the literatures for the right hip joint center (HJC) coordinates in the pelvis (dimensions shall be in mm), Harrington, 2007).

	Davis, 1991	Bell, 1990	Software for OrthoTrak, Motion Analysis Corp., (CA, USA)
HJC-x	$-0.95\mathrm{X_{dis}} + -0.031\ \mathrm{LL} - 4$	-0.19 PW	-0.22 PW
HJC-y	$-0.31\mathrm{X_{dis}} - 0.096\ \mathrm{LL} + 13$	-0.14 PW	-0.34 PW
HJC-z	$0.5\mathrm{PW} - 0.055\ \mathrm{LL} + 7$	0.30 PW	0.32 PW

Delivered generalized regression equations by Harrington et al. (2007), in mm.

$\hat{x}(\text{anteriordirection}) = -0.24PD - 9.9$……........……...…………...(2.1)

$\hat{y}\ (\text{distal direction}) = -0.30PW - 10.9$…………………….………(2.2)

$\hat{z}$ (medial direction) $= 0.33PW + 7.3$……………………..………...(2.3)

Authors concluded that delivered generalized regression equations could improve estimates based on existing predictive methods by up to 7 mm, depending on method and direction. However, predictive methods do not account for pelvic asymmetry and do not account for errors in marker placement or skin movement artifacts.

2.4.3 COMPARISON OF REGRESSION EQUATIONS AND DIFFERENT FUNCTIONAL METHODS IN THE LITERATURE

1- In 1999, Leardini et al. validated a functional method for the estimation of HJC location. Their research determined the accuracy with which the subject specific coordinates of the hip joint center in a pelvic anatomical frame can be estimated using different methods. The functional method was used by calculating the center of the best sphere described by the trajectory of markers located on the thigh during several trials of hip rotations. Different prediction methods which estimate the HJC of adult subjects applying regression equations and anthropometric measurements were also considered. The accuracy of each method evaluated with respect to the results obtained from eleven able-bodied male adults using roentgen stereophotogrammetric analysis, which is assumed to yield the exact HJC locations. The average root mean square (RMS) distance of estimated HJC location by prediction methods was 25-30 mm. The performance of the functional method (when hip motion range of the subject is not limited) was significantly better with RMS distance of 13 mm.

2- In a research by Sangeux et al. (2011), the accuracy of HJC localization from two sets of regression equations (Davis, 1991 and Harrington, 2007) and five different functional methods (Piazza, 2001; Cappozzo, 1999; Piazza, 2004; Ehring, 2006; Global calibration method based on study of Lu, 1999 and Charlton, 2004) compared against 3-D ultrasound data.

According to the results, geometric sphere fitting technique (by applying 6 markers on the thigh), with mean absolute distance error of 15 mm (85% of measurements were within 20 mm), performed better than the other methods. Also widely used regression equations perform particularly badly whereas the most recent equations (presented by Harrington, 2007) performed very closely to the best functional method with a mean absolute error of 16 mm (88% of measurements were within 20 mm).

2.5 OVERVIEW OF PRESENTED METHODS IN THE LITERATURE

The accuracy of the functional method of HJC estimation is not satisfactory when hip joint motion is limited but somehow a limited type of movement proved to give better results for elderly and some pathologic subjects (as shown by Piazza et al. in 2004) than large motion amplitude (performing VHM trial). Increasing the number of motion data observations and analyzing the motion of a single thigh marker was not found to increase error, significantly. Increasing the duration of the motion performed had very little effect on HJC location accuracy also the accuracy can be improved by associating different types of movement.

All functional methods can produce accurate measures under rigid body conditions but there are many differences between methods in deformable conditions. The error would be dramatically lower when using the distal marker clusters.

Because of lower accuracy of predictive methods, another approach may be introduced by combining these methods as proposed by Bell in 1990. For simplicity it is suggested to use pelvic width, height and depth parameters to optimize HJC location relative to the true location of HJC

(Seidel, 1995), but measurement of pelvic height is not possible without MRI, USI or X-ray techniques.

Results from regression analysis and validation techniques on the MRI data suggested (Harrington, 2007) that the best predictors of HJC location were: pelvic depth for the antero-posterior (x) direction; pelvic width and leg length for the supero-inferior (y) direction; and pelvic depth and pelvic width for the medio-lateral (z) direction.

Leardini, 1999 and Sangeux, 2011 compared the functional and predictive methods and concluded that functional method yields better results than predictive methods but predictive methods could perform very closely to the best functional method like method presented by Harrington (2007).

CHAPTER 3
METHODOLOGY

3.1 SUBJECTS, EQUIPMENT AND SOFTWARE

This study was performed in Middle East Technical University, Department of Mechanical Engineering Biomechanics Laboratory by using Gait Analysis System (Kiss) and Atatürk Research and Education Hospital Radiology and Orthopeadics and Traumatology Clinics. The software packages used were 3Dslicer 3.6 (The Slicer community), Solidworks® (Version 2009, Dassault Systèmes SolidWorks Corp.), Matlab® (Version 7.1.0.246 R14, the MathWorks Inc., MA, USA) and METU Biomechanics Laboratory locally developed data acquiring (Kiss-DAQ) and analysis (Kiss-GAIT 6 and Kiss-GaitM). Eight healthy young male subjects (age: 24.5 ± 3.38 years, weight: 75.6 ± 7.82 kg, stature: 173 ± 3.02 cm) participated in this research. During this study, all subjects were voluntarily selected and the experiments were performed under the approval of the Ethics Committee of METU.

3.2 METU BIOMECHANICS LABORATORY

METU Biomechanics laboratory consists of a Gait Analysis System named as **KISS**, which is an abbreviation for "**Ki**nematic **S**upport **S**ystem" in English and "***K**as **İ**skelet **S**istemi*" in Turkish. This is the first gait analysis system founded in Turkey, utilizes off-the-shelf equipment and its own locally developed data acquisition and analysis software for motion analysis. In the laboratory, besides clinical gait analysis studies which are performed in cooperation with medical doctors, research projects, master's and Ph.D. thesis carried out in various fields of motion analysis and biomechanics.

3.2.1 LABORATORY HARDWARE

Six charge-coupled device (CCD) cameras (Ikegami Electronics, Inc., Maywood, NJ, USA) with sampling frequency of 50 Hz are positioned around the laboratory, and used for kinematic data acquisition. These cameras are equipped with infrared light emitting diodes (LED) and infrared-pass filters, track reflecting light from passive markers placed on the subject. A video triggering unit designed by TÜBİTAK–Bilten (Ankara, Turkey) and produced by ODESA Inc. (Ankara, Turkey) is utilized for the synchronization and storage of camera data.

Modified Helen Hayes marker set is applied in experiments with marker radius of 12.7 mm (1/2 inches). The markers are wooden balls coated with 3M® (St. Paul, MN, USA) retro reflective material. Three types of markers are used in the marker set (Figure 7).

a) Marker type 1 b) Marker type 2 c) Marker type 3

Figure 7 Three types of markers which are used in the marker set.

Force measurement unit consists of two force plates, two amplifiers and a data acquisition card. Strain gauge based force plates of type 4060 HT (Bertec Corporation, Columbus, OH, USA) are embedded in staggered form in the 4.6 m walkway for acquisition of ground reaction forces and moments. Two 6-channel amplifiers (type AM6-3, Bertec Corporation, Columbus, OH, USA) are employed for amplification of voltage output from the force plates. The data acquisition card, NI AT-MIO-64E-3 (National Instruments, Austin, TX, USA) converts analog signals to digital data.

Before starting experiments, camera calibration is performed by the use of calibration rods equipped with 24 markers of known positions. To correct lens distortion errors in camera images, frequently a linearization grid is employed.

3.2.2 LABORATORY SOFTWARE

Kiss-DAQ and **Kiss-GAIT** are two locally developed programs constituting the software part of **KISS**. Data acquisition during gait trials is performed by **Kiss-DAQ** program. The software is capable of calibration and linearization of the cameras, as well as synchronous recording of camera images with force plate and electromyography (EMG) data (if required). Identification and generation of marker trajectories in Kiss-DAQ program is an off-line process. **Kiss-GAIT** software calculates time-distance parameters, joint angles, joint moments and joint powers from an input file that combines marker trajectories and force plate data, along with anthropometric measurements taken from the subject.

3.3 LABORATORY EXPERIMENT PROCEDURE

A normal gait experiment at METU gait analysis protocol is composed of the following steps:

3.3.1 LINEARIZATION

Due to camera lens distortions (the cameras in the laboratory are security cameras with wide angle lenses and high distortions) marker image coordinates recorded by the cameras are different from real marker coordinates. Therefore, a correction must be performed on recorded coordinates before the calibration process. For this purpose, a linearization process is employed for all cameras.

3.3.2 CAMERA CALIBRATION

The cameras need to be calibrated before each gait experiment session. The purpose of this calibration process is to relate 2-D marker image data on each camera image plane to its 3-D counterpart by performing calculations based on known 3-D marker coordinates within the calibration volume enclosed by four calibration rods.

3.3.3 STATIC TRIAL

Main purpose of static trial is to perform anatomical landmark calibration. By this procedure, certain anatomical landmarks like the joint centers, which cannot be identified by direct marker attachment, can be located relative to markers. Figure 8 shows markers attached on subject during static trial from frontal view (the heel markers which are attached on the posterior segment of the feet are not visible). Static trial data acquisition duration is one second without any kinetic data acquisition.

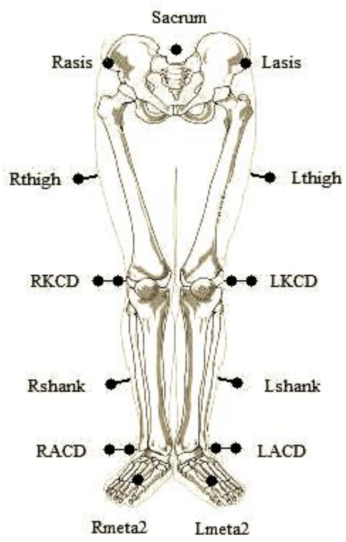


Figure 8 Marker Placements in Static Trial (adapted from Kafalı, 2007).

3.3.4 DYNAMIC TRIAL

Dynamic trial is the second part of the experiment. Heel markers and centering devices are removed from the subject after static trials. Type 3 markers are placed on lateral femoral epicondyles and lateral malleoli (Figure 9). Positions of all other markers remain identical in both static and dynamic trials.

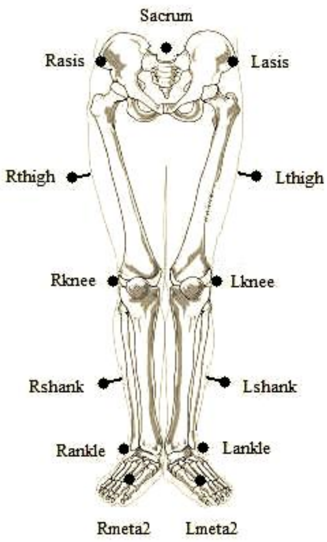


Figure 9 Marker Placements in Dynamic Trial (adapted from Kafalı, 2007).

3.3.5 ANTHROPOMETRIC MEASUREMENTS

Anthropometric data of the subject is used together with marker coordinates in estimation of joint centers, segment mass centers, and mass moment of inertias of the segments for kinematic and kinetic calculations. The following anthropometric measurements are taken in a regular gait experiment:

1- ASIS-ASIS Distance: Distance between right and left anterior superior iliac spines.

2- Leg Length: Leg length, measured from ASIS to medial malleolus, passing through medial femoral epicondyle (for both legs).

3- Knee Width: Distance between medial and lateral femoral epicondyles. Knee width is measured for both sides.

4- Ankle Width: Distance between medial and lateral malleoli. Ankle width is measured for both sides.

5- Mass: Body mass of the subject

6- Height: Height of the subject

3.3.6 PROCESSING EXPERIMENTAL DATA

Many in-house software packages are employed in METU gait analysis protocol for processing and analyzing image data and force plate data collected in experiments.

i. Raw image data obtained from six cameras are first processed by the **Motion Tracking** program embedded in **Kiss-DAQ**. This program performs grouping of pixels for the identification of markers and constructs 3-D marker coordinates (Shafiq, 1998). Afterwards, marker images are interactively labeled by user and marker trajectories are constructed. This process is performed for both static and dynamic trials.

ii. In the next step, **Bvd Filer** program combines the results of previous step into a single file.

iii. **Kiss-GAIT** program reads the created bvd file along with anthropometric measurements from the subject, and calculates temporal, kinematic and kinetic gait parameters via utilization of a biomechanical model (Güler 1998). Computed kinematic and kinetic parameters can be plotted as a function of percentage of gait cycle. Kiss-GAIT program furthermore enables the user to save computed gait parameters such as static angles, raw and smoothed joint angles, joint moments, joint powers, etc. in text format.

A more detailed discussion on laboratory hardware and software is presented in the Ph. D. dissertation by Güler (1998) and M. Sc. thesis by Kafalı (2007) and more explanation on linearization, calibration and laboratory experiment procedure could be found in the M. Sc. thesis by Kafalı (2007).

3.4 JOINT KINEMATICS CALCULATIONS

Calculation of kinematic gait parameters from stereophotogrammetric data requires utilization of methods of classical mechanics together with biomechanical models that represents the human body as a mechanical system.

Joint kinematics calculations of Kiss-GAIT software was reformulated by Afşar (2001) and Söylemez (2002). The methodology and formulations presented by Söylemez (2002) were applied in computer code by Kafalı in 2007. The aim of that study was the adaptation of some joint center estimation methods to METU Kiss protocol and investigation of joint center location effects on kinematic results. Primary step in Kafalı's thesis was regeneration of previous joint kinematics calculations employed by Kiss protocol. Successfully re-generating kinematic results of the old Kiss protocol with the computer code in Matlab® resulted in modifications on calculation procedure. The purpose of modifications was to investigate joint kinematics. The joint kinematics calculation procedure of Kiss-GAIT and its theoretical background is presented by Kafalı (2007) and detailed formulations are provided by Söylemez (2002).

3.5 PROCEDURE FOR JOINT KINEMATICS CALCULATIONS

Main steps of the joint kinematics calculation procedure utilized in the METU gait analysis protocol are presented in the following sections.

3.5.1 MARKER COORDINATE TRANSFORMATION

Marker coordinates are reconstructed from raw camera data in Kiss-DAQ. Since reference frames employed by Kiss-DAQ and Kiss-GAIT are different, firstly, these marker coordinates should be transformed into Kiss-GAIT coordinate system.

3.5.2 DATA FILTERING

Before kinematic calculations, 3-D marker data must be filtered in order to eliminate noise contained in the data. A second order Butterworth type filter (with cut-off frequency of 6 Hz) is applied for this purpose (Güler, 1998 and Kafalı, 2007).

3.5.3 SEGMENTAL REFERENCE FRAME CONSTRUCTION

Instantaneous positions and orientations of lower extremity segments are calculated by the use of segment-fixed reference frames, which are constructed from coordinates of markers attached on the segment. Subsequent calculations for joint kinematics are based on these segment-based frames.

Kiss protocol uses joint coordinate system definitions proposed by Grood and Suntay (1983). Joint kinematics calculations require utilization of anatomical segment reference frames which are defined according to the anatomical planes of segments. The utilization of the anatomical reference frames in joint angle calculations yields clinically meaningful joint angles. Construction of these anatomical reference frames entails determination of certain anatomical landmark positions such as knee and ankle joint centers, which are located in static trial by use of anatomical landmark calibration methods.

For each segment, technical and anatomical reference frames are constructed from static trial data. Assuming that all segments are rigid, transformation between the two frames is considered to remain constant at all times. In dynamic trials only technical reference frames can be constructed from the recorded data. The constant transformation between anatomical and technical frames is used to obtain anatomical reference frames at each time instant in dynamic trials. Detailed explanation about technical and anatomical reference frames of each segment and their constructions are presented by Kafalı (2007) and Güler (1998).

3.6 COMPUTER CODE FOR KINEMATIC CALCULATIONS RE-GENERATION

A computer code with a Graphical User Interface (GUI) was developed by Kafalı in Matlab® (Version 7.1.0.246 R14, the MathWorks Inc., MA, USA) for re-generation of the joint kinematics calculations. The developed GUI reads text files containing static and dynamic trial marker coordinates and anthropometric data of the subject.

3.7 HIP JOINT CENTER ESTIMATION METHODS ADAPTED IN METU KISS PROTOCOL

Like all motion analysis systems that employ stereophotogrammetric techniques, joint kinematics and kinetics calculations performed in METU Gait Analysis System are also directly affected from errors in determination of joint centers. Söylemez (2002) investigated results of hip joint center mislocation and effects of varying centering device placement on joint kinematics outputs of Kiss protocol. Kafalı (2007) concluded that kinematic results were significantly affected from variations in joint center coordinates. Three different hip joint center estimation methods available in literature were employed by Kafalı (2007) as presented below:

1- The predictive approach as presented by Davis et al. (1991) (which is the method used by METU gait analysis system).

2- Two functional approaches for determining hip joint center

i- An iterative sphere fitting algorithm, which computes hip joint center from trajectory of the knee joint center in pelvic reference frame.

ii- Utilization of pelvis and thigh reference frames to identify hip joint center location using linear least squares approach.

3.8 GAIT EXPERIMENTS

Performances of joint center estimation methods adapted to Kiss protocol were investigated through gait experiments. Experiments were performed with eight healthy male subjects with no previous history of musculoskeletal injury or illness. One set of trial session was performed for each subject, implementing joint center estimation methods. In the first part of the experiment a standard static trial was carried out, in which centering devices were employed for identification of knee and ankle axes then the experiment continued by normal walking known as dynamic trial or gait trial. Gait trials were performed for 5 or 6 seconds while the subjects walked along the walkway at a self-selected pace.

3.9 MRI DATA ACQUISITION

For determining the location of HJC as precise as possible (close to exact location), MRI data acquisition procedure was selected because MRI does not contain ionizing radiation unlike computed tomography but still can supply detailed information about 3D anatomy. MRI of pelvis and femur heads were obtained at the Atatürk Research and Education Hospital Department of Radiology for each subject after performing laboratory experiments in the same day (Figures 10 and 11). MRI data were acquired by Philips, Achieva, 1.5 T, (Netherlands) with T1 weighted, coronal (T1W) and 2 mm of slice thickness.

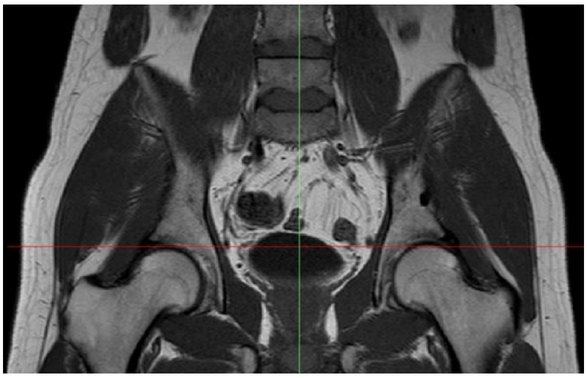
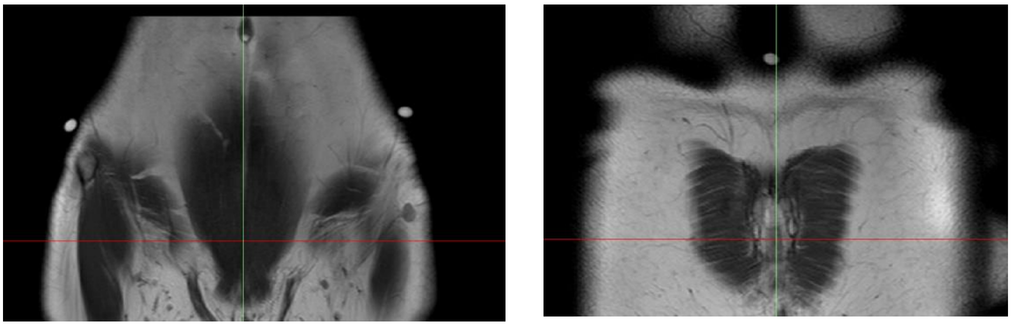


Figure 10 One slice of MR image of pelvis in Atatürk Research and Education Hospital Department of Radiology (data belongs to subject AB).

For comparing the results of MRI and laboratory gait analysis data the pelvis coordinate system in both experiments needs to be identical but because of marker placement on the skin, segmentation and sphere fitting process in the related programs the results will have some error. To determine the pelvis coordinate system in MRI data, the locations of base of sacrum and ASIS markers in gait analysis were marked immediately after gait experiment with fish oil tablet using adhesive tape, which is visible in MRI (Figure 11) and at the same day the subjects with fish oil tablet on his skin were took to the hospital to obtain MRI data.

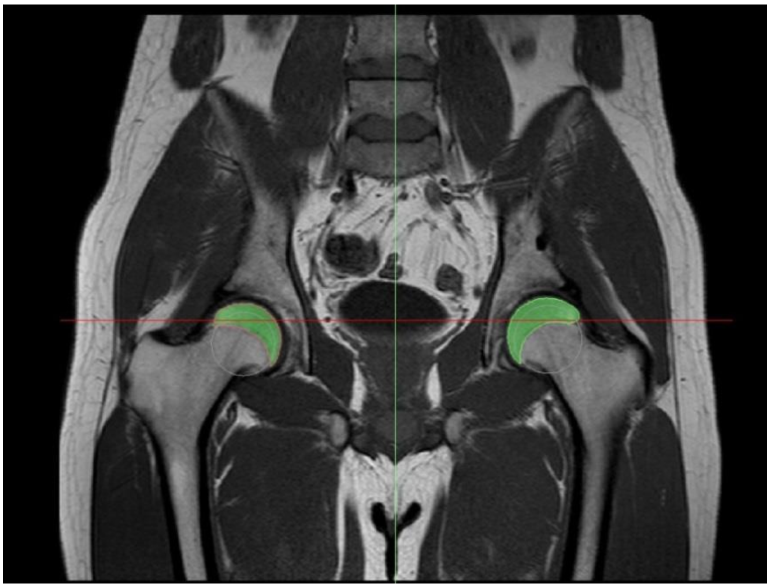


a) b)

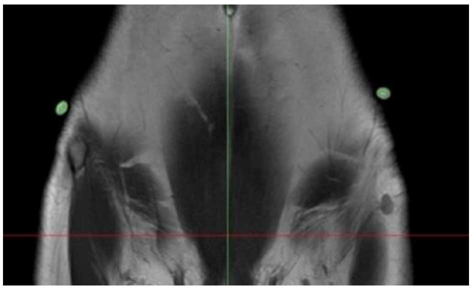
Figure 11 ASIS (a) and Sacrum (b) markers are applied for defining pelvis coordinate system and are visible in MRI data (data belongs to subject AB).

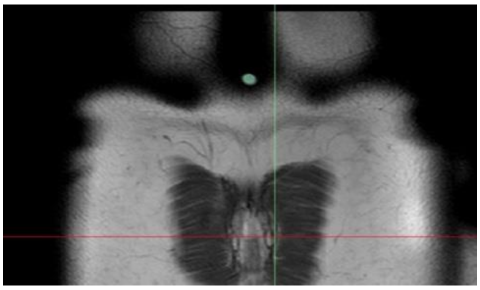
The steps of fitting sphere and creating CAD file are as follows:

1- MRI data was obtained in DICOM format from Atatürk Research and Education Hospital.
2- DICOM files were read by the 3Dslicer 3.6 to generate three-dimensional models of ASIS markers, sacrum marker, pubic symphysis and femur heads.
3- A mask is created by segmentation from pubic symphysis, ASIS markers, sacrum marker and femur heads (rounded part of the femoral head). The created mask only contains bones of the subjects (head of the femur, and markers attached on the skin) but not soft tissue. Other parts are erased (Figure 12).



a)

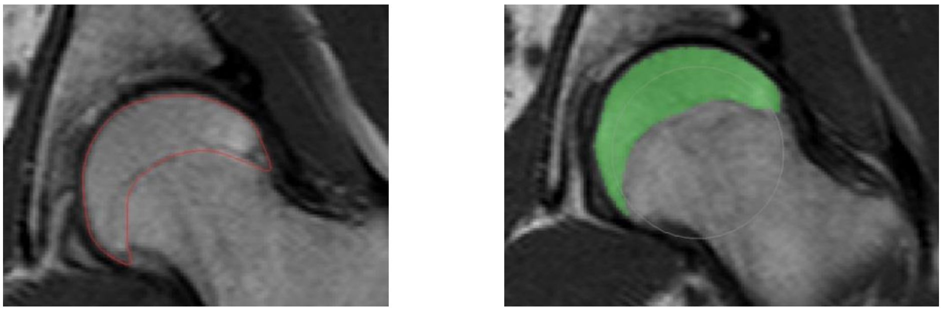




b) c)

Figure 12 Segmentation and fitting sphere on femur heads (a), the ASIS markers (b), and sacrum marker (c) (data belongs to subject AB).

For sphere fitting process it is noted that head of the femur is spheroidal rather than spherical. The boundary of femoral head (the boundary which head of the femur is close to spherical shape) were selected as suggested by Dr. Nurdan Çay (radiologist at Atatürk Research and Education Hospital), (Figure 13).



a) b)

Figure 13 Selected boundary of rounded part of the left femoral head (a) and segmentation, created mask and fitted sphere (b).

4- The command 'calculate 3D from mask' executed (Figure 14).

Figure 14 Created 3D model from mask.

5- According to procedure of the 3Dslicer 3.6 program for sphere fitting, a polynomial calculated from 3D model of each subpart (pubic symphysis, ASIS markers, sacrum marker and femur heads) by "calculate polynomials" command. The sphere fitting process of 3Dlicer is fully automated without any intervention by the user therefore it is believed that this process is objective.

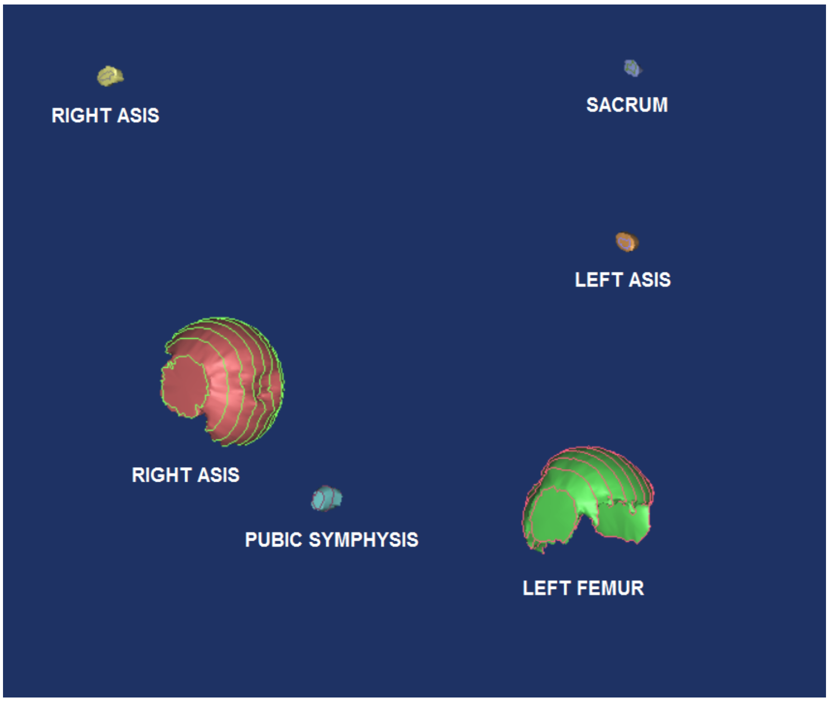
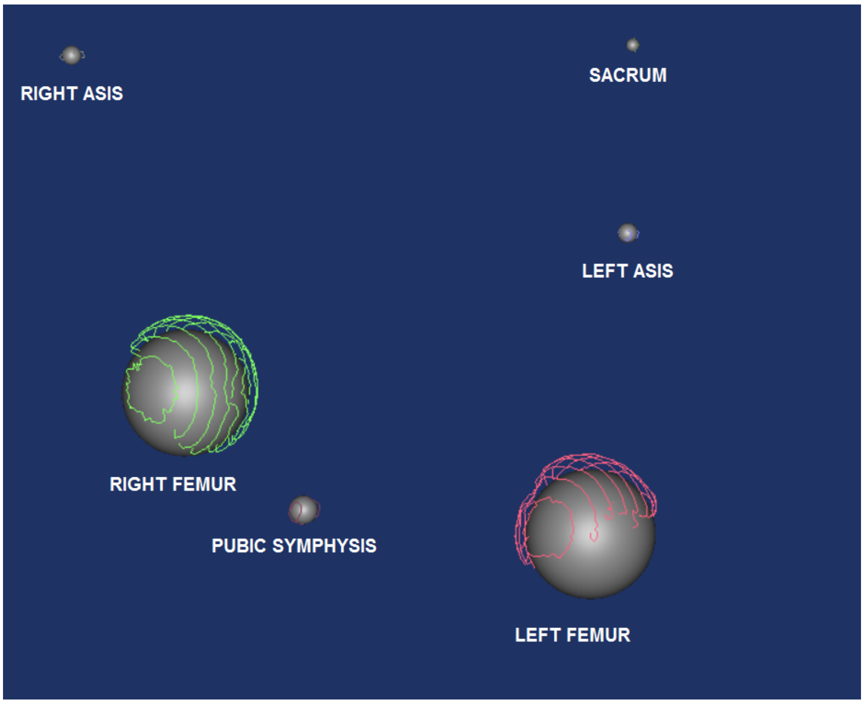
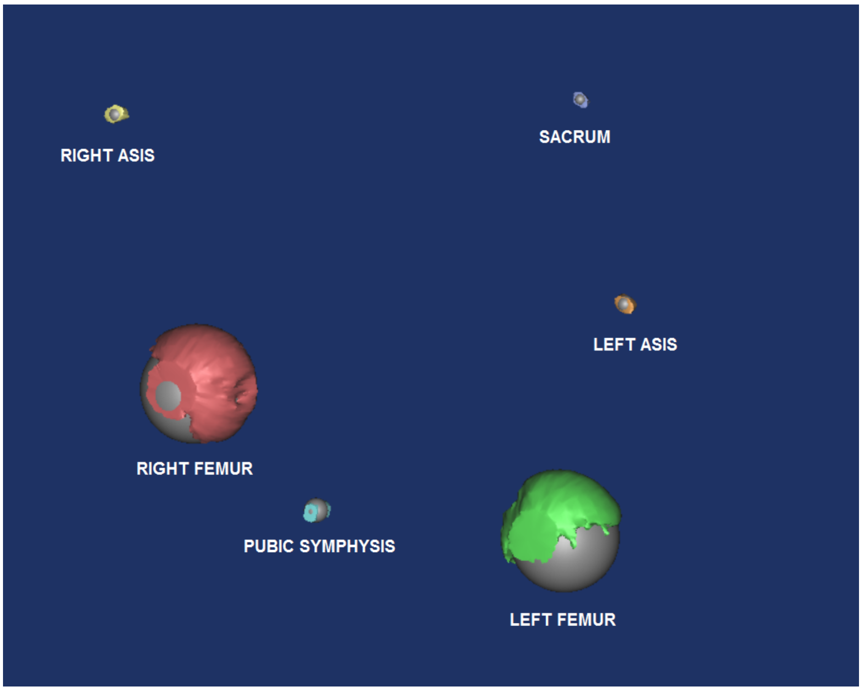


Figure 15 Calculated polynomial from 3D model of each subpart.

6- A sphere is fitted by the fit a sphere command in the created polynomial on each subpart, pubic symphysis, ASIS markers, sacrum marker and femur heads (Figure 12). Subparts created in the mask by segmentation do not have a regular shape because MRI equipment gets images slice by slice. 3Dslicer 3.6 program automatically fits sphere on the selected polynomials where again there is no user intervention. It is concluded that, the precision of fitting process and fitted sphere depends on the created polynomials and the created polynomial depends on how the user creates the masks of each subpart and head of the femur in step 3 which may be subjective (Figure 15).



a)



b)

Figure 16 Fitted sphere to the calculated polynomials (a) hiding polynomials and showing 3D model and fitted spheres.

7- All fitted spheres known as CAD objects in the program are exported to a CAD file in IGS format. This CAD file consists of pubic symphysis, ASIS markers, sacrum marker and femur heads (Figure 17).

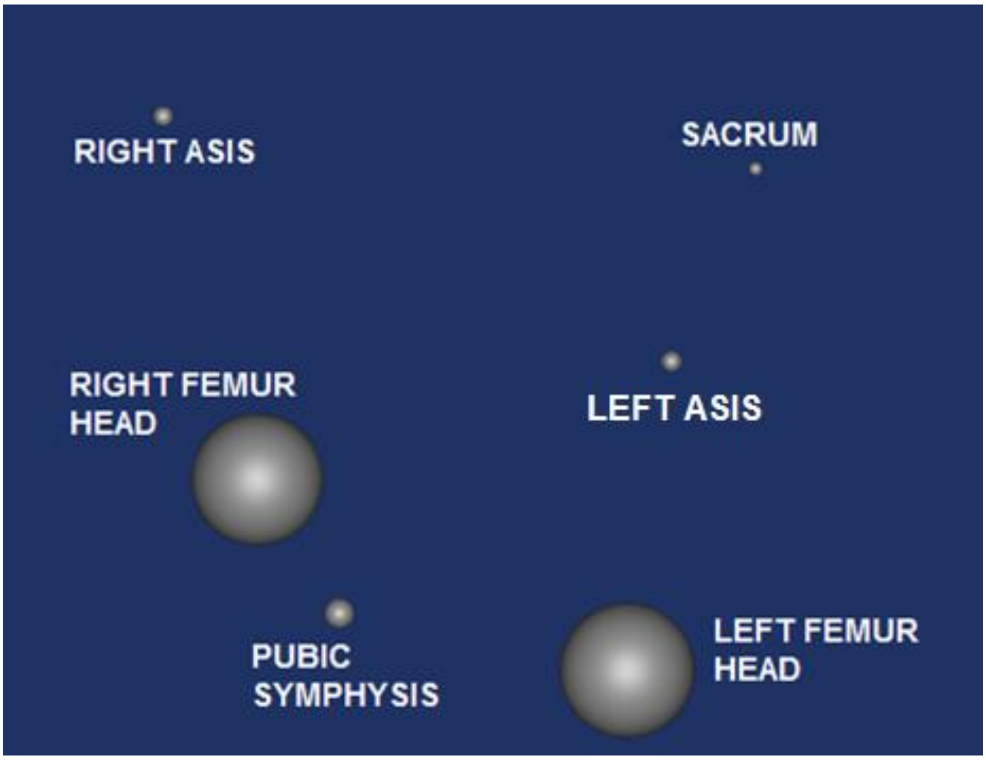


Figure 17 The CAD file which consists of spheres fitted on the subparts (data belongs to subject AB).

3.10 ANALYSIS OF EXPERIMENTAL DATA

Data analysis is divided into two parts, gait experiment data analysis and MRI data analysis. In gait experiment data analysis, for each trial, recorded camera data were first processed by motion tracking program to reconstruct three dimensional marker trajectories. This information was then converted into text format and read by the Matlab® GUI code together with anthropometric measurements of the subject. Gait events were identified interactively for the analyzed gait trial. After determination of the gait events, a new window for determination of joint centers using the adapted methods were opened with the "Joint Center Trajectories" button (details are presented by Kafalı, 2007).

MRI data received in DICOM format form the Atatürk Research and Education Hospital, was opened by 3Dslicer 3.6 to create three dimensional models of heads of the femurs, pubic symphysis and to identify the location of the markers on the sacrum, right and left ASIS. A sphere is fitted on each of the parts created by segmentation, and the results are saved as IGS format as a CAD file. The CAD data is imported to Solidworks® program. Pelvic coordinate system in MRI data and gait analysis data are matched in three stages as presented:

First stage

1- The coordinates of markers, right and left ASIS and sacrum, are extracted from static trial of the laboratory gait analysis and saved as text file in laboratory coordinate system.
2- The coordinates are input to Solidworks® program using 3-D sketch command.
3- Coordinate data are saved as a Solidworks® part format (Figure 18).

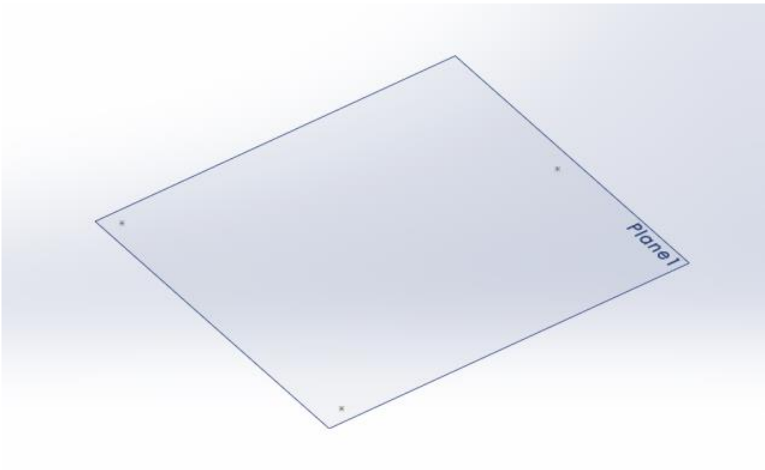
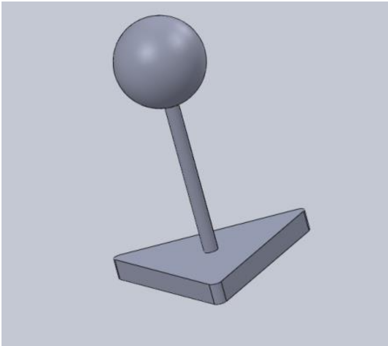
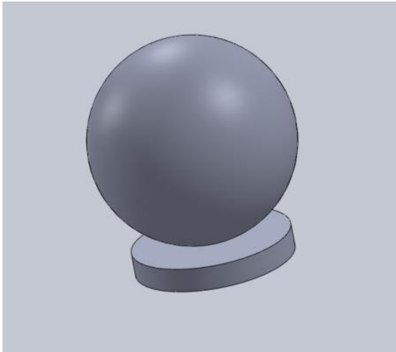


Figure 18 Coordinates of right and left ASIS and sacrum markers.

4- An assembly format file is created from Solidworks® part format by using the command: make assembly from the part.
5- 3-D parts of sacrum and ASIS markers (marker type 1 and type 3) are created in Solidworks® program (Figure 19) and merged to the

assembly file created in step 4 by using the command: insert part to the assembly.





a) Marker type 1 b) Marker type 3

Figure 19 3-D model of marker type 1 and 3.

6- Mate the center of rounded part of each created marker in step 5 to its related position in the assembly file ASIS marker to ASIS coordinates and sacrum marker to sacrum coordinate. This step should be done by ‘’Mate’’ command in the Solidworks® program which results a unique answer.

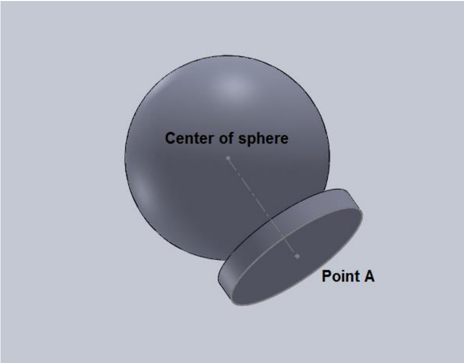
Second stage

1- The IGS file created by 3Dslicer 3.6 is opened in Solidworks® program.
2- A point is created at the center of each sphere in the opened IGS file which corresponds to the ASIS and sacrum markers on the skin.
3- Data are saved in Solidworks® part format.

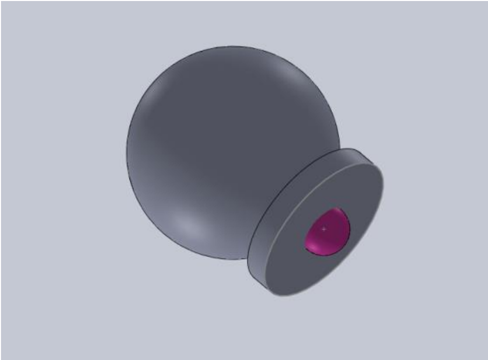
Third stage

1- The resulting data of second stage is inserted to the assembly file of first stage using the command: insert part to the assembly.
2- On left and right side, point A, the point of the base of the marker which is in contact with subject’s skin, on the marker type 3 is made coincident

using ‘’Mate’’ command to the center of sphere which fitted to the ASIS on the skin (Figure 20).



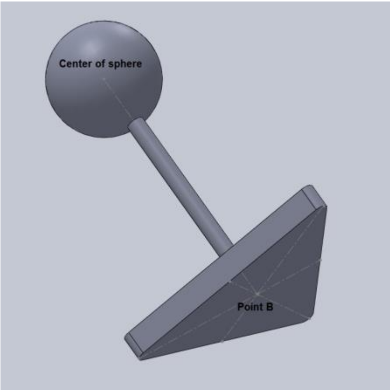
a. Point A on the marker type 3.



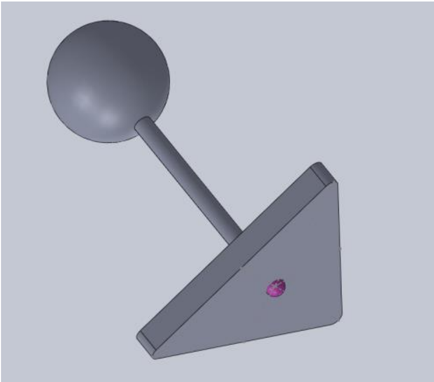
b. Mating point A on the marker type 3 to the center of ASIS fitted sphere on the skin.

Figure 20 Mating fitted spheres to the marker type 3.

3- Point B, the point of the base of the marker which is contact with subject’s skin, on the marker type 1 is made coincident, using ‘’Mate’’ command, to the center of sphere which fitted to the sacrum on the skin (Figure 21).



a. Point B on the marker type 1.



b. Mating point B on the marker type 1 to the center of sacrum marker on the skin.

Figure 21 Mating fitted spheres to the marker type 1.

4- A line from the center of sphere of marker type 3 and type 1 to point A in both ASIS and sacrum markers (Figure 22) is drawn.

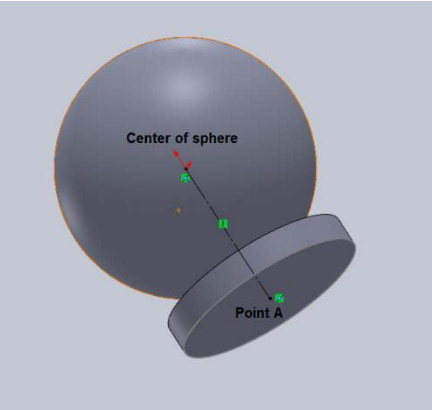


Figure 22 The drawn line from the center of sphere of markers type 3 to pint A and type 1 to point B.

5- In the assembly file, the created line in markers type 3 is made horizontal (Figure 22).

Through above three stages two models are matched and single pelvis coordinate system (Figure 23) could be defined for both gait analysis and MRI data. Using the coordinates of the sacrum, right and left ASIS, extracted from the static data of gait experiments, and the marker type 1 and type 3 created in Solidworks® program, the difference between gait and MRI coordinates were minimized. In pelvis coordinate system (Figure 23) Y axis is perpendicular to pelvis plane defined by sacrum and ASIS markers and ASIS-ASIS line is created from centers of ASIS markers.

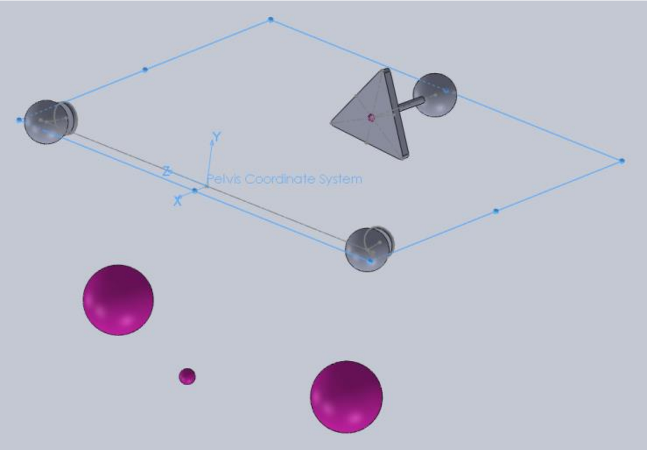
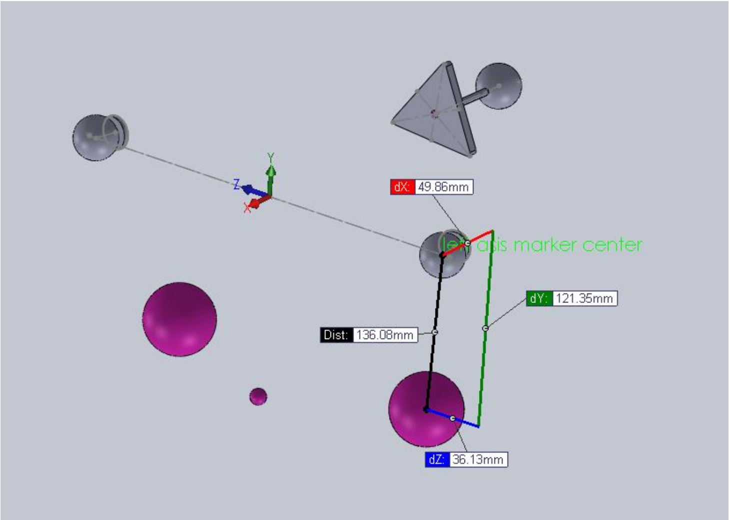
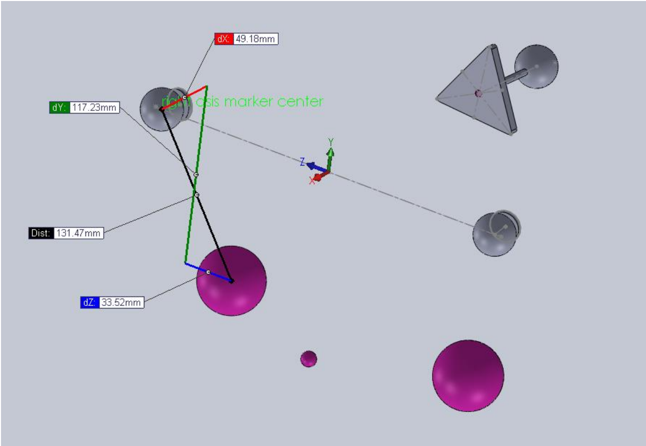


Figure 23 Pelvis coordinate system, which created by pelvis plane and ASIS-ASIS line.

In the next step location of each HJC (right and left) with respect to pelvis coordinate system and ASIS markers is extracted in three dimensions (Figure 24 and Figure 25).

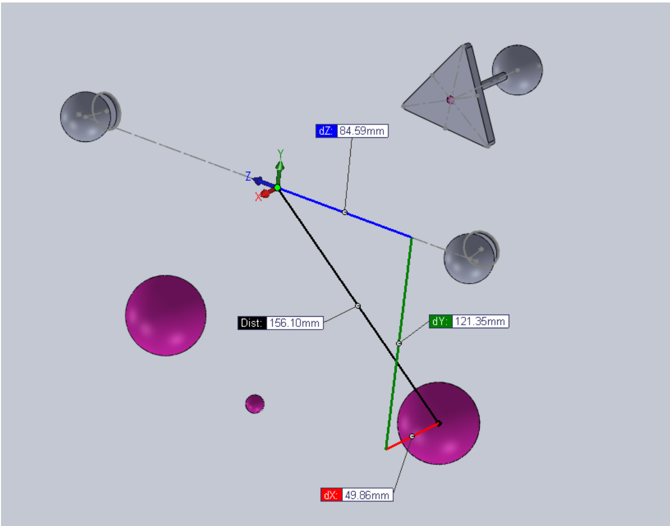


a) Location of left femur head center with respect to left ASIS marker center.

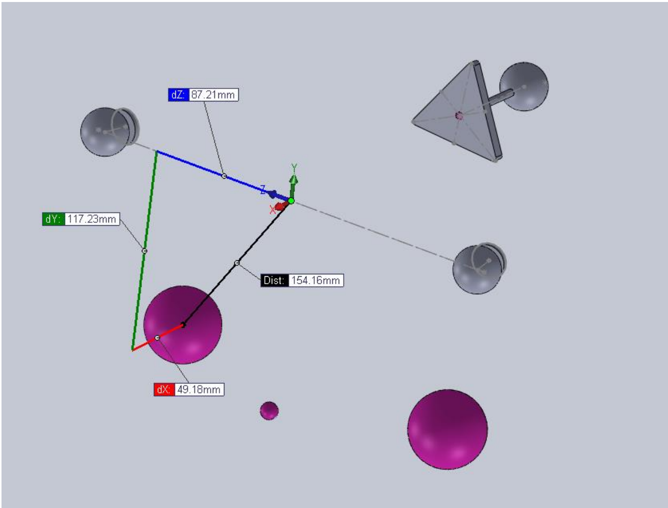


b) Location of right femur head center with respect to right ASIS marker center.

Figure 24 Location of Hip Joint Center (femur head center) with respect to ASIS markers in pelvis coordinate system (data belongs to subject AB).



a) Location of left femur head center with respect to pelvis coordinate system center.



b) Location of right femur head center with respect to pelvis coordinate system center.

Figure 25 Location of Hip Joint Center (femur head center) with respect to pelvis coordinate system center (data belongs to subject AB).

The procedure described in this chapter is to create a single pelvis reference frame applicable for the MRI data and gait analysis results in the laboratory. For this purpose the location of ASISs and sacrum markers are matched in MRI and gait analysis data in a unique manner.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

METU gait analysis system utilizes Davis (1991) method to estimate HJC for kinematic and kinetic analysis of human locomotion. Davis method is a fully predictive method, which relies only on anthropometric measurements of the subject and regression equations based on previous studies.

The goal of this study is to evaluate various methods of HJC estimation including Davis method, present a procedure to match MRI data to gait analysis protocol, analyze and criticize the results. Four widely used anthropometric methods and two functional methods of HJC estimation available in literature are compared with MRI data which is assumed to be the golden standard.

Eight healthy young male subjects with anthropometric measurements given in Table 8 were selected for this study. Anatomical landmarks (ASISs, PSISs, sacrum, pubic symphysis and HJC) and geometrical measurements of pelvis (pelvis width, pelvis depth and pelvis height) applicable in most of the anthropometric methods are presented in Figure 6. The sacrum landmark is in the mid-point of the line connecting PSISs.

Table 8 Anthropometric measurements of the subjects.[1]

Subject	AB	HP	BR	GC	SC	SI	MT	MC	AVE.
ASIS-ASIS (mm)	251	240	266	263	279	246	267	275	257.12
RLL (mm)	920	900	970	880	900	880	910	1000	920
LLL (mm)	920	900	970	880	900	880	910	1000	920
RKW (mm)	95	86	98	90	100	98	87	90	93
LKW (mm)	95	86	98	90	100	98	87	90	93
RAW (mm)	52	51	53	55	60	55	48	58	54
LAW (mm)	52	51	53	55	60	55	48	58	54
Weight (kg)	64	79	85	73	80	68	71	85	75.63
Stature (m)	1.72	1.70	1.73	1.70	1.75	1.71	1.72	1.79	1.73
Age	22	29	28	20	22	23	24	28	24.5

4.1.1 SELECTED ANTHROPOMETRIC METHODS

Tylkowski method (presented in 1982 and modified twice by Bell in 1989 and 1990), Davis method (introduced in 1991), two methods presented by Seidel et al. (1995) and formulation presented by Harrington et al. (2007), are anthropometric methods considered in this study.

[1] RLL: Right Leg Length, LLL=Left Leg Length, RKW=Right Knee Width, LKW=Left Knee Width, RAW=Right Ankle Width, LAW=Left Ankle Width.

4.1.2 SELECTED FUNCTIONAL METHODS

Kafalı (2007) adapted the two functional methods, linear least squares algorithm (LSA) proposed by Piazza et al. (2004) and iterative sphere fitting algorithm (SFA) presented by Hicks and Richards (2005), into the METU gait analysis protocol and compared the results by Davis method. However the results obtained were not evaluated with more precise data like MRI. The experiments carried out with three healthy subjects performing different types of motions (standing leg motion and normal walking). In this work, the adapted functional methods in METU gait analysis system are compared to the MRI results.

4.2 ANTHROPOMETRIC METHODS

4.2.1 METHOD OF TYLKOWSKI et al (1982) AND MODIFICATION TWICE BY BELL (1989 and 1990)

Tylkowski et al. presented the location of hip joint center in percent of pelvis width (PW, also known as ASIS-ASIS distance) in three anatomical directions. Table 9 presents results of Tylkowski's method in 1982 and modification of this method by Bell in 1989 and 1990.

Table 9 Results of Tylkowski group, its modification by Bell and MRI results.

METHOD	Posterior direction x (% PW)	Medial direction z (% PW)	Distal direction y (% PW)
Results of Tylkowski (1982)	21	11	12
Bell et al. (1989) modified Tylkowski's Approach	22	14	30
Bell et al. (1990) modified Tylkowski's Approach	19.3	14.1	30.4

According to the procedure explained in Chapter 3, pelvis reference frame utilized in MRI data is the same with the one used by Tylkowski. The midpoint of ASIS-ASIS distance is the origin of the coordinate system, ASIS-ASIS line is Z axis (positive toward right side), Y axis is perpendicular to the plane defined by ASIS markers and sacrum marker (positive upward) and X axis is perpendicular to Z and Y directions forming right handed orthogonal coordinate system. Table 10 presents the HJC location of eight subjects evaluated from MRI, which are presented in percent of ASIS-ASIS distance (%PW).

Table 10 Hip Joint Center of eight subjects presented in percent of ASIS-ASIS distance of the same subject.

Subject	PW (mm)	Posterior direction- x (% PW)	Medial direction- z (% PW)	Distal direction- y (% PW)
AB	251	19.76	15.73	47.06
HP	240	20.97	12.33	43.02
BR	267	22.76	16.91	36.62
GC	264	14.91	15.21	49.67
SC	279	17.14	16.28	43.35
SI	246	18.91	13.28	43.13
MT	267	16.24	17.54	42.53
MC	275	18.27	18.88	42.55
Total average	-	18.62	15.77	43.49
S.D.	-	2.39	2.02	3.54

Assuming improvement in determining HJC from 1982 to 1990, the results presented by Bell in 1990 was considered to be more reliable than the results of Tylkowski and Bell in 1989. Differences between the results of MRI method (total average in Table 10) and second modification of Bell show that in posterior and medial directions this method yields better results (the difference is 0.68% of PW in posterior and 1.67% of PW in medial direction) compared to the distal direction (the difference is 13.09% of PW).

In addition, one can understand from comparing the results of Tylkowski and Bell and MRI results in Table 11, that the locating the HJC in each direction is improved from one study to the next. Table 11 presents the individual and average difference (in mm) in each direction with respect to MRI results.

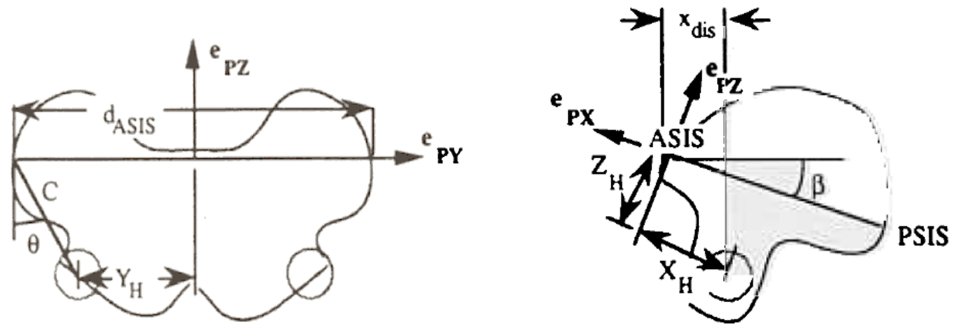
Table 11 Individual and average difference of Bell's method (1990) in millimeters with respect to MRI results in three directions

Subject	Difference in Posterior direction-x (mm)	Difference in Medial direction-z (mm)	Difference in Distal direction-y (mm)
AB	1.15	4.09	41.82
HP	4.00	4.25	30.29
BR	9.23	7.50	16.60
GC	11.58	2.93	50.87
SC	6.02	6.08	36.13
SI	0.95	2.02	31.32
MT	8.17	9.18	32.38
MC	2.83	13.14	33.41
Average differences	5.50	6.16	33.41
S.D.	4.04	3.24	15.16

The average differences in posterior and medial directions are 5.50 mm in posterior and 6.16 mm in medial direction. According to Stagni et al. (2000) the method is reliable and can be applied in these two directions. However, the average difference in distal direction is 33.41 mm; obviously the error in the results of joint kinetic and kinematic data will be much higher, so it is not recommended to apply this method in this direction.

4.2.2 METHOD PRESENTED BY DAVIS

The basic formulation for the Davis (1991) method is shown in Figure 26. This method for the first time was introduced at Newington Children's Hospital in 1981 through the radiographic examination of 25 hip studies. The current protocol of METU gait analysis protocol uses Davis' method to locate hip joint center.



a) Coronal Plane View b) Sagittal Plane View

Figure 26 The formulation of the Davis (1991) method, (adapted from Davis, 1991).

Formulation of this method for Kiss is presented by Söylemez (2002) as follows:

$$X_H = [-x_{dis} - r_{marker}]\cos\beta + C\cos\theta\sin\beta \quad (4.1)$$

$$Z_H = [-x_{dis} - r_{marker}]\sin\beta - C\cos\theta\cos\beta \quad (4.2)$$

$$Y_H = -\sigma[C\sin\theta - \frac{d_{ASIS}}{2}] \quad (4.3)$$

where

$$C = 0.115L_{leg} - 15.3 \quad (4.4)$$

$x_{dis} = 0.1288L_{leg} - 48.56$ (4.5)

$\beta = 18°$, $\theta = 28.4°$

$r_{marker} = 12.7\ mm$ (Marker radius)

$\sigma = +1$ For the right extremity and $\sigma = -1$ for the left extremity

L_{leg} : Leg length, in mm

d_{ASIS}: Distance between right and left ASISs in mm

The results of Davis formulation (average of right and left legs) and its difference with respect to MRI data for the eight subjects are shown in the Table 12.

Table 12 The results of Davis method and its difference with respect to MRI data.

-	Posterior direction- x (mm)		Medial direction- z (mm)		Distal direction- y (mm)	
Subject	Davis	Difference	Davis	Difference	Davis	Difference
AB	56.84	9.44	81.96	4.11	102.18	19.17
HP	55.02	0.6	78.05	12.48	99.45	5.49
BR	61.41	1.12	87.22	6.06	108.98	4.52
GC	53.20	10.70	90.64	1.16	96.73	35.90
SC	55.02	5.92	97.55	3.42	99.45	23.47
SI	53.19	6.54	82.14	8.28	96.74	10.56
MT	55.93	2.24	90.50	10.60	100.82	6.86
MC	64.14	13.63	90.08	4.49	113.06	3.96
Average difference		6.27		6.33		13.74
S.D.		4.46		3.60		10.73

Like Tylkowski method and modifications by Bell, Davis method is also more accurate in posterior (average difference 6.28 mm) and medial (average difference 6.33 mm) directions than the distal direction with respect to MRI data. Despite more inaccuracy in distal direction with respect to MRI data, the precision of Davis method in this direction (with 13.74 mm difference and S.D. 10.18 mm) is better than the Tylkowski and Bell methods (with 34.31 mm difference).

4.2.3 METHODS PRESENTED BY SEIDEL

Seidel (1995) defined the frontal plane as the plane passing through both ASISs and the pubic symphysis. The coordinate system was defined with its origin at the respective ASIS side (line passing right and left ASISs) being measured: z-axis mediolateral, along ASIS-ASIS line (positive medial), y-axis superodistal and on the frontal plane created by ASIS marker and pubic symphysis (positive upward), and x-axis (anteroposterior) forms right handed orthogonal coordinate system (positive posterior), (Figure 27).

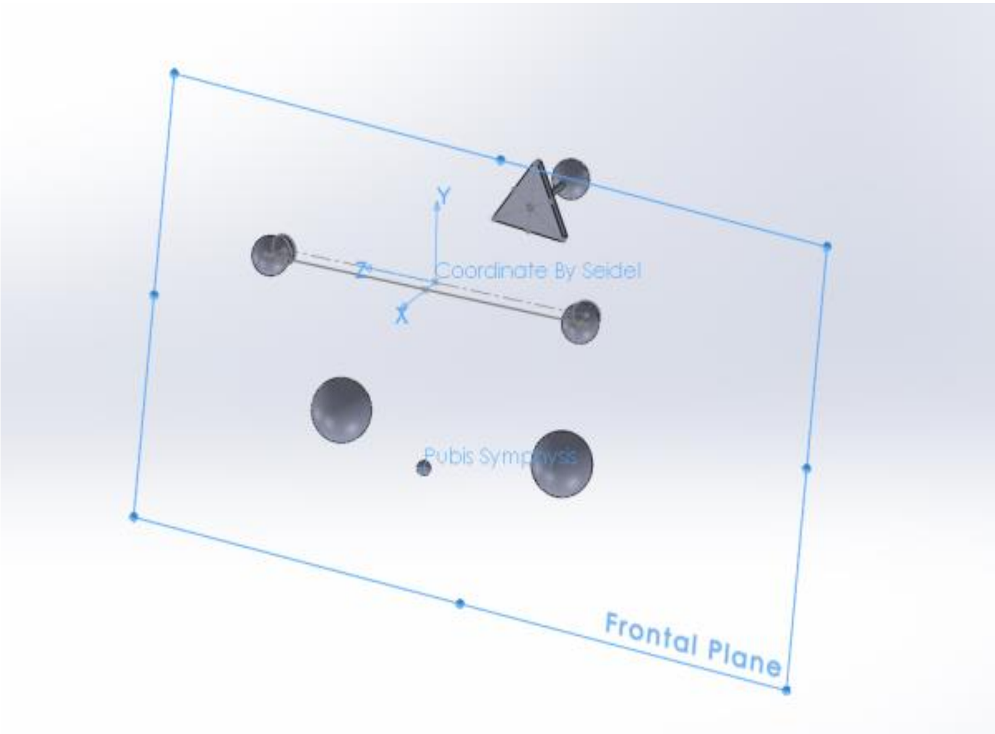


Figure 27 The coordinate system defined by Seidel (1995).

Seidel presented hip joint center location with two different methods: first he presented hip joint center in all directions as percent of ASIS-ASIS distance (PW), (here stated as Seidel's first method). Secondly he presented hip joint center location in medial direction as percent of ASIS-ASIS distance (PW), in distal direction as percent of pelvis height (PH) and in posterior direction as percent of pelvis depth (PD), (here stated as Seidel's second method). For Seidel's first method, the hip joint center location with respect to ASIS location is expressed in percentage of ASIS distance (%PW) of the same subject in all three direction (Table 13, data shows the average of right and left legs).

Table 13 Hip joint center location with respect to ASIS location is expressed in percent of ASIS distance of the same subject (Seidel's first method).

Subject	PW (mm)	Posterior direction- x (% PW)	Medial direction-z (% PW)	Distal direction- y (% PW)
AB	251	19.73	15.70	47.53
HP	240	21.00	12.34	43.10
BR	267	22.58	17.61	36.61
GC	264	14.71	15.40	49.84
SC	279	17.16	16.29	43.38
SI	246	18.92	13.30	43.21
MT	267	16.21	17.45	42.51
MC	275	18.05	18.72	41.48

Differences between the MRI results and Seidel method (Table 14) reveal that like the results by Bell (1990), Siedel's first method yields better results in posterior and medial directions (5.77% in posterior and 2.19% in medial direction of ASIS distance) than the distal direction (13.74% PW).

Table 14 Difference between the MRI results and hip joint center in all directions as percent of ASIS-ASIS distance presented by Seidel's first method

	Posterior direction-x (% PW)	Medial direction-z (% PW)	Distal direction-y (% PW)
Results presented by Seidel 1995	24	14	30
Total average of MRI data	18.23	16.19	43.74
Magnitude of Difference	5.77	2.19	13.74
S.D. of MRI data (Table 13)	3.01	1.13	3.62

For second method of Seidel, the hip joint center location in distal and posterior direction, with respect to ASIS location is expressed in percentage of Pelvis Height (PH) and Pelvis Depth (PD) of the same subjects (Table 15, data shows the average of right and left legs).

In this method, the results (Table 15) of HJC location in distal direction are better than his first method with a difference of 4.93% of PH (the difference varies from 4.24 mm to 6.52 mm) but the problem here is about obtaining PH which is not easy without invasive methods. For posterior direction the difference is 7.39%, which is larger than the methods by Davis (1991) and Bell (1990).

Table 15 Pelvis Height (PH), Pelvis Depth (PD) and Location of HJC with respect to Pelvis Height and Pelvis Depth in distal and posterior directions.

Subject	PH (mm)	Distal direction-y (%PH)	PD (mm)	Posterior direction-x (%PD)
AB	125.51	88.68	145.51	46.53
HP	103.97	78.22	182.46	47.44
BR	120.81	62.19	202.74	41.62
GC	129.56	95.49	149.21	42.87
SC	130.60	85.05	170.18	42.30
SI	119.61	83.41	154.46	39.65
MT	121.59	88.54	143.63	40.52
MC	132.30	89.89	174.26	30.17
Total average	-	83.93	-	41.39
Seidel 1995	-	79	-	34
Average Difference	-	4.93	-	7.39
S.D.	-	9.48	-	4.95

4.2.4 METHOD PRESENTED BY HARRINGTON

Harrington et al. (2007) analyzed Davis (1991), Bell (1990) and software recommendations for OrthoTrak, Motion Analysis Corp., (CA, USA) methods and recommended an optimal method. Formulation of his method based on pelvis width (PW) and pelvis depth (PD) is as follows:

$$X_H = -0.24PD - 9.9 \quad (4.6)$$

$$Z_H = 0.33PW + 7.3 \quad (4.7)$$

$$Y_H = -0.30PW - 10.9 \quad (4.8)$$

Table 16 presents results of Harrington (2007) formulation in eight subjects and the MRI results for the same subject. This method yields the highest difference in distal direction. The results are better in posterior (with 5.80 mm difference) and medial (with 7.76 mm difference) directions.

Table 16 Results of Harrington (2007) formulation in eight subjects and the MRI results for the same subject (dimensions are in mm).

	Posterior direction-x		Distal direction-y		Medial direction-z	
Subject	Harrington	MRI	Harrington	MRI	Harrington	MRI
AB	44.82	49.52	86.20	119.29	90.13	86.07
HP	53.69	50.41	82.90	103.43	86.50	90.53
BR	58.56	60.29	91	97.74	95.41	81.16
GC	45.71	38.84	90.10	131.59	94.42	91.80
SC	50.74	45.45	94.6	121.05	99.37	94.13
SI	46.97	32.72	82.90	106.29	86.5	90.42
MT	44.37	53.48	91	113.49	95.41	79.90
MC	51.72	50.50	93.4	117.02	98.05	85.59
Average error	5.80		24.73		7.76	

4.3 FUNCTIONAL METHODS

4.3.1 LINEAR LEAST SQUARE ALGORITHM (LSA) PROPOSED BY PIAZZA

The method is based on minimization of a cost function using a linear least squares approach (Appendix B). Results of HJC location estimated by least square algorithm and its difference with respect to MRI results in three directions are expressed in Table 17.

Table 17 Hip Joint Center of eight subjects using least squares algorithm (LSA) and the difference with respect to MRI data (dimensions are in mm).

Subject	Leg	Posterior direction-x (mm)		Medial direction-z (mm)		Distal direction-y (mm)	
		LSA	Diff.	LSA	Diff.	LSA	Diff.
AB	Right leg	51.57	4.32	73.51	7.94	79.51	18.36
	Left leg	46.18	0.78	121.94	5.72	93.95	22.04
HP	Right leg	54.84	5.74	97.55	6.99	80.90	8.31
	Left leg	74.54	0.76	105.34	0.06	39.88	4.15
BR	Right leg	56.48	3.54	121.40	23.67	100.10	0.21
	Left leg	48.69	19.17	140.19	21.8	106.42	1.56
GC	Right leg	56.04	16.05	79.70	1.76	138.16	33.72
	Left leg	54.87	12.27	87.06	0.26	107.07	36.38
SC	Right leg	48.8	4.71	33.99	0.44	95.81	26.07
	Left leg	45.47	1.4	132.10	2.32	136.71	23.76
SI	Right leg	62.99	8.02	87.99	0.54	33.7	15.27
	Left leg	52.3	4.88	108.06	5.13	96.53	7.42
MT	Right leg	58.48	1.28	79.88	7.16	74.44	7.29
	Left leg	60.01	0.89	60.23	6.65	65.07	6.19
MC	Right leg	55.19	4.43	73.18	11.75	93.17	25.76
	Left leg	53.28	3.03	55.02	31.23	95.01	20.11
Average Error	-	-	5.71	-	8.34		16.04

According to average difference, this method performs better in posterior and medial directions. In distal direction, the results (with 16.04 mm difference) are close to the results by Davis (with 13.74 mm difference).

4.3.2 ITERATIVE SPHERE FITTING ALGORITHM (SFA) PRESENTED BY HICKS and RICHARDS

Results of HJC location estimated by sphere fit algorithm (Appendix B) and its differences with respect to MRI results in three directions are expressed in Table 18.

Table 18 Hip Joint Center of eight subjects, results of Sphere Fit Algorithm and the difference with respect to MRI data (dimensions are in mm).

-	-	Posterior direction-x (mm)		Medial direction-z (mm)		Distal direction-y (mm)	
Subject	Leg	SFA	Diff.	SFA	Diff.	SFA	Diff.
AB	Right leg	51.5	4.39	79.43	13.86	101.07	39.92
	Left leg	46.83	1.43	90.49	37.17	101.23	29.32
HP	Right leg	50.78	1.68	80.83	9.73	98.34	25.75
	Left leg	53.96	19.82	93.31	12.09	99.07	63.34
BR	Right leg	54.54	1.6	98.16	46.91	107.85	7.54
	Left leg	43.33	13.81	109.63	52.36	102.83	5.15
GC	Right leg	59.13	12.96	94.59	13.13	98.64	5.8
	Left leg	54.20	12.94	91.02	3.7	96.52	25.83
SC	Right leg	52.58	0.93	90.56	56.13	97.05	27.31
	Left leg	51.72	4.85	100.46	33.96	98.95	14
SI	Right leg	53.55	17.46	84.83	2.62	96.23	77.8
	Left leg	52.64	4.54	90.34	12.59	95.67	6.56
MT	Right leg	57.32	0.12	88.48	1.44	100.78	33.63
	Left leg	58.62	2.28	85.13	18.25	101.09	42.21
MC	Right leg	55.36	4.6	86.12	1.19	110.86	8.07
	Left leg	53.56	3.31	74.91	11.34	113.01	2.11
Average Diff.	-	-	6.66	-	20.40	-	25.90

This method shows better performance in posterior direction than the other two directions. Because of more average error in medial and distal directions, this method will contain more error in calculating kinetic and kinematic properties of joints (Stagni et al., 2000).

4.4 COMPARISON OF METHODS

By comparison of all anthropometric and functional methods, it is concluded that none of these methods could predict HJC accurately in all three directions. Generally, all methods give acceptable results in posterior and medial directions, except SFA by Hicks and Richards (Table 19). In distal direction, only two methods (Davis and LSA by Piazza) yield results with less difference compared to MRI results.

Table 19 Evaluation of presented methods (the data are average of differences and are with respect to MRI data and are in mm).

Method	Difference in posterior (x) direction	Difference in distal (y) direction	Difference in medial (z) direction
Bell (1990)	5.50	33.41	6.16
Davis (1991)	6.17	13.76	6.33
Seidel (1995), first method	14.93	35.75	6.77
Seidel (1995), second method	12.21	35.33	6.06
Harrington (2007)	5.80	24.73	7.76
LSA by Piazza (2004)	5.71	16.04	8.34
SFA by Hicks and Richards (2005)	6.66	25.90	20.40

Of all methods of HJC estimation evaluated here, in x direction method presented by Bell gives less difference than the other methods, even better than functional methods. Second option, which can be applied in this direction could be one of Davis, Harrington or LSA presented by Piazza. In y direction Davis method or LSA could be used. Most of the methods give good results in z direction but it may be arranged in order of increasing complexity: Bell, Davis, Seidel's first method, Seidel's second method, Harrington and LSA by Piazza.

The results in Table 19 also show that in posterior and medial directions anthropometric methods predict hip joint center better than functional methods. In medial direction, the difference between functional methods and anthropometric methods decreases (especially with LSA by Piazza). Considering all three directions, among two functional methods, LSA by Piazza and from anthropometric methods Davis method is preferred to apply and between these two methods, Davis method has least differences.

None of the methods is accurate in all three directions, to achieve optimal kinematic and kinetic results a combination of methods could be analyzed and compared by considering simplicity, reliability and performance of methods in all direction. In the hybrid method, for posterior direction, the method presented by Bell (1990) has selected (19.30% of PW). For medial direction first method of Bell (1990) which predicts hip joint center as 14.1% of PW medially, is applied. For distal direction Davis (1991) or LSA by Piazza (2004) method could be selected to analysis. For some clinical and gait analysis applications (other than research purpose), because of its simplicity, Davis method is selected.

CHAPTER 5

JOINT KINEMATICS RESULTS OF ADAPTED HYBRID METHOD

5.1 INTRODUCTION

As presented in the Chapter 4, the results of Davis method applied in METU gait analysis system have some differences with respect to MRI results. The differences between Davis method, combination of methods and MRI are small which may not have much effect on the kinematic and kinetic properties of joints, only it may have effect in y (distal) direction (because of greater difference)

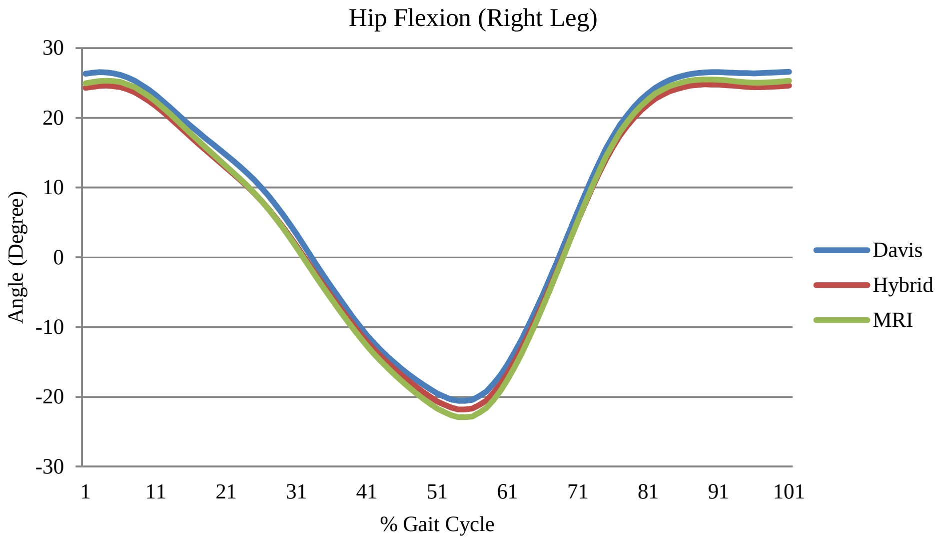
In this chapter a combined method has analyzed, criticized and compared with Davis and MRI methods. The combined method of HJC estimation is composed of Bell (1990) and Davis (1991) methods. In this method, in posterior (x) direction, the method presented by Bell predicting HJC as 19.30% of PW; in distal (y) direction Davis method (currently employed) and in medial direction (z) Bell's method are preferred (Table 20). In this thesis because of less differences between these methods, a new method of HJC estimating was not presented. A combination of selected methods was compared to the results MRI and Davis methods.

Table 20 Combination of methods selected for analyses.[2]

Method	Posterior direction- x	Medial direction- y	Distal direction- z
Bell, 1990	19.30%PW	-	-
Davis, 1991	-	$[-PW - r_{marker}]\sin\beta - C\cos\theta\cos\beta$	-
Bell, 1990	-	-	14.1%PW

[2] $\beta = 18°,\ \theta = 28.4°$, $C = 0.115L_{leg} - 15.3$, $L_{leg}$is leg length and $\sigma = +1$ for the right extremity and $\sigma = -1$ for the left extremity.

Figure 24 to 29 represent the results of joint kinematic data of hip and knee using MRI, Davis, and combination (hybrid) of methods. Since all subjects have the similar results, only the results of subject AB presented here as an example in the study. Changing hip joint center coordinates influences directly hip and knee joint angles.



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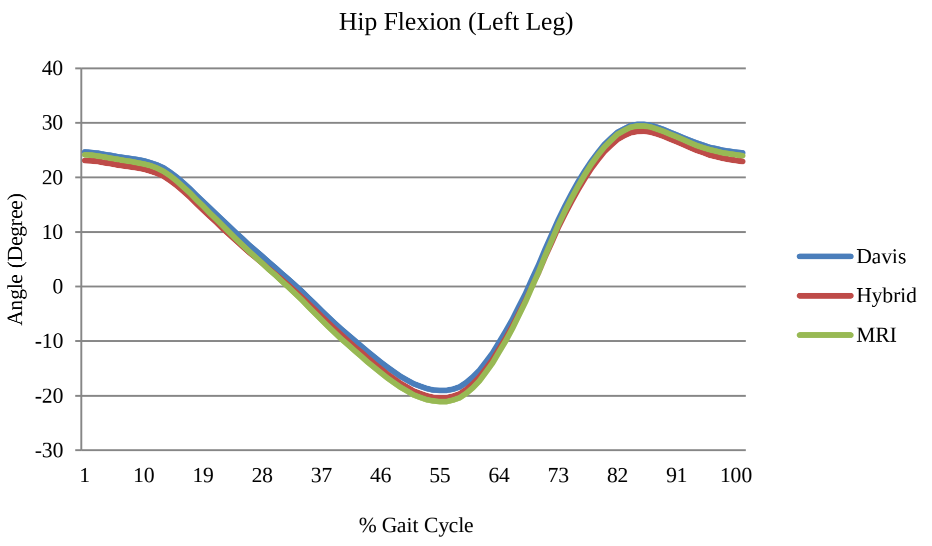
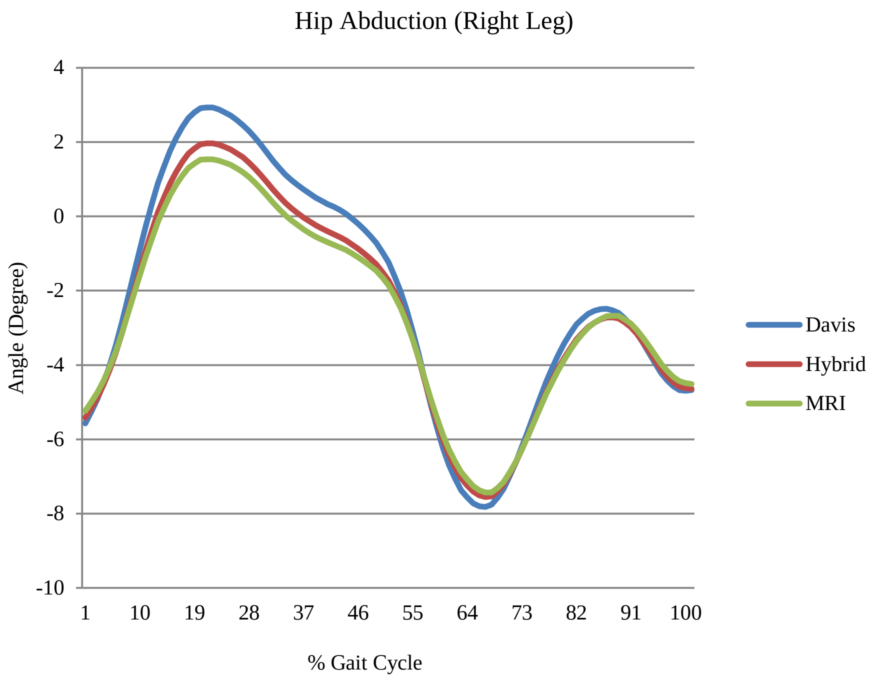


b)

Figure 28 Smoothed Right/Left Hip Flexion

The results of hip flexion for both right and left leg for all three methods are close to each other (Figure 28).



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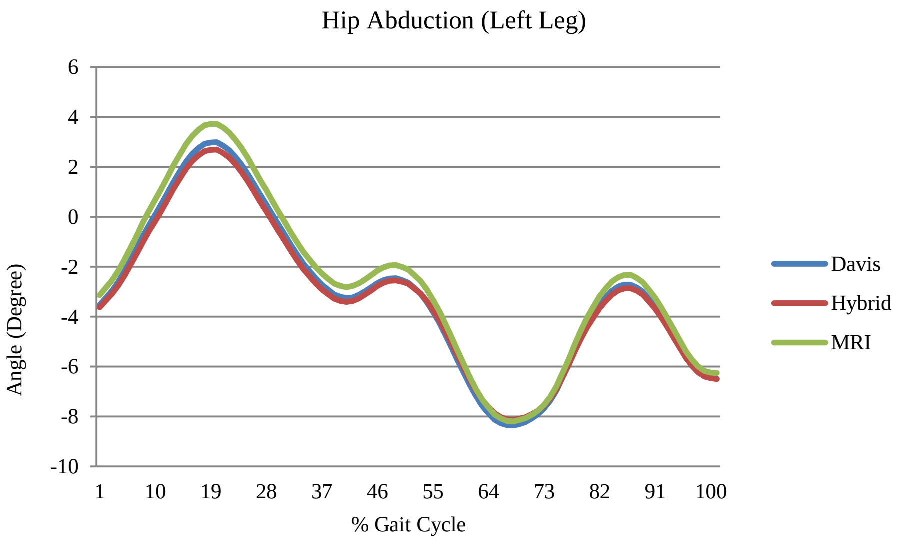
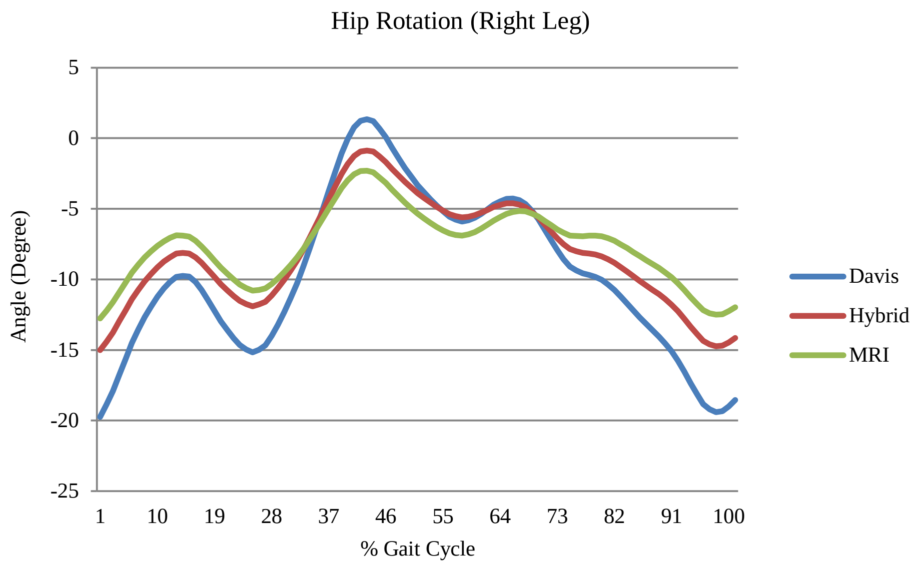


b)

Figure 29 Smoothed Right/Left hip abduction.

The results of hip abduction like hip flexion are close to each other in three methods (Figure 29), especially for the left leg, which in this case Davis method is close to MRI results.



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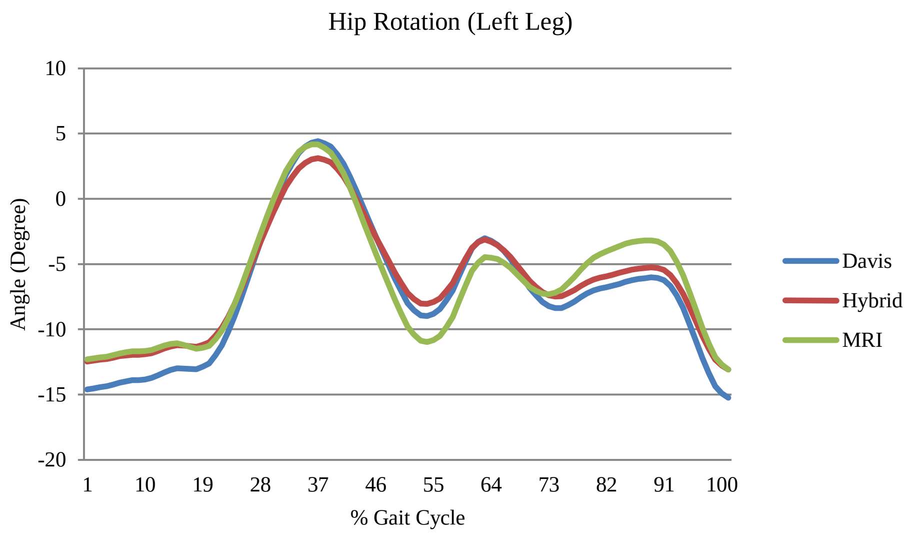
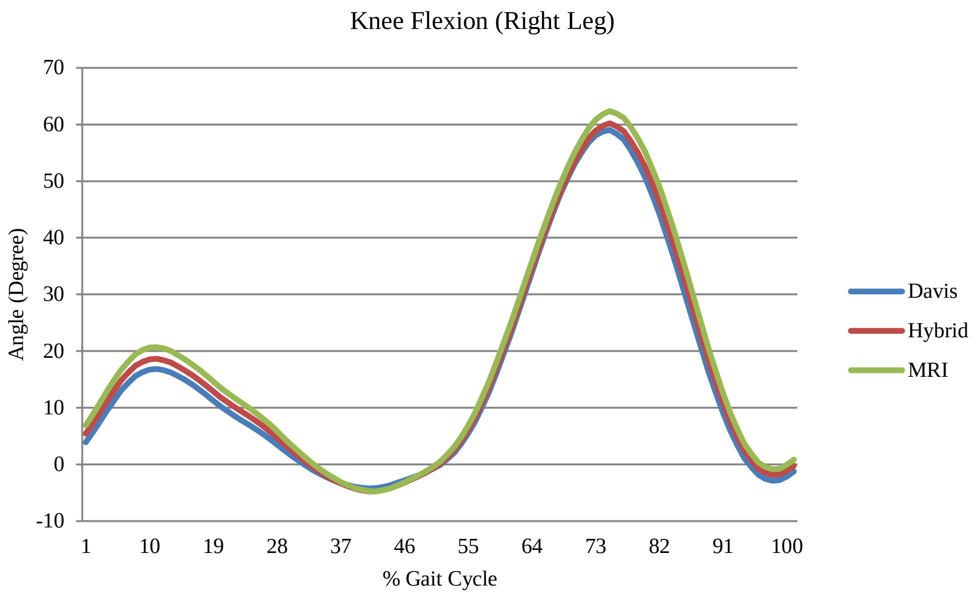


b)

Figure 30 Smoothed Right/Left Hip Rotation

For the hip rotation (Figure 30), at the beginning and end of the gait cycle the difference between the methods has the maximum value. In between 30% and 75% of the gait cycle, the difference becomes less.



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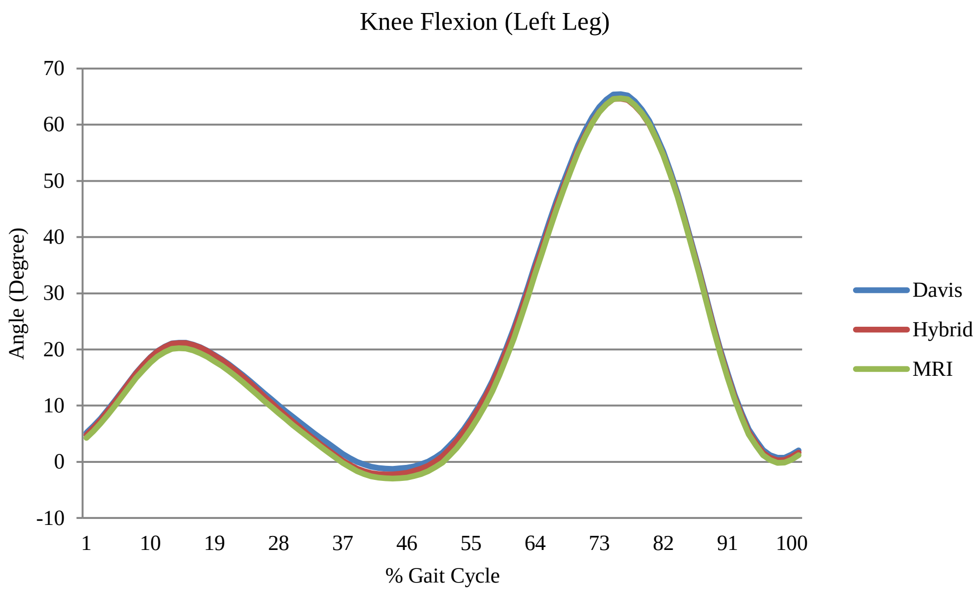
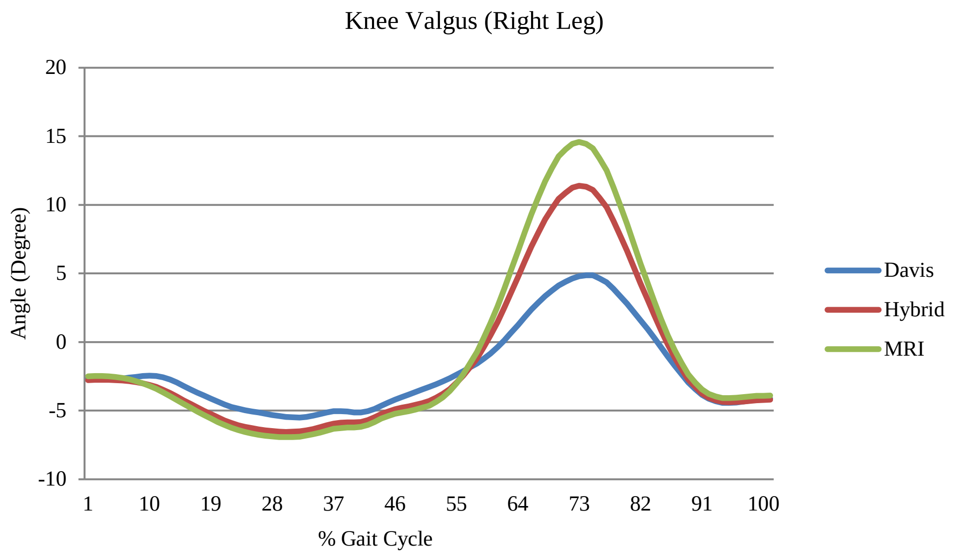


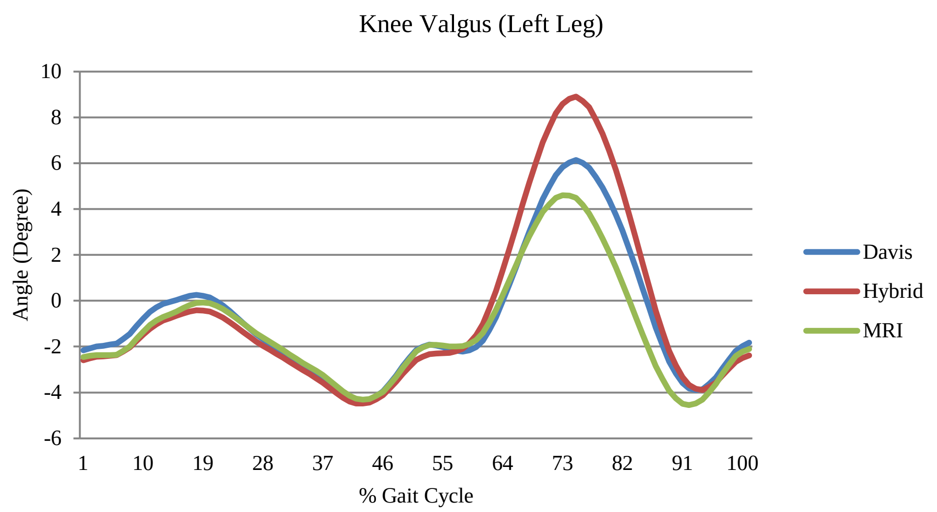
b)

Figure 31 Smoothed Right/Left Knee Flexion

The results of knee flexion in three methods have the least difference (close to MRI) among all other data (Figure 31), especially for the left leg.



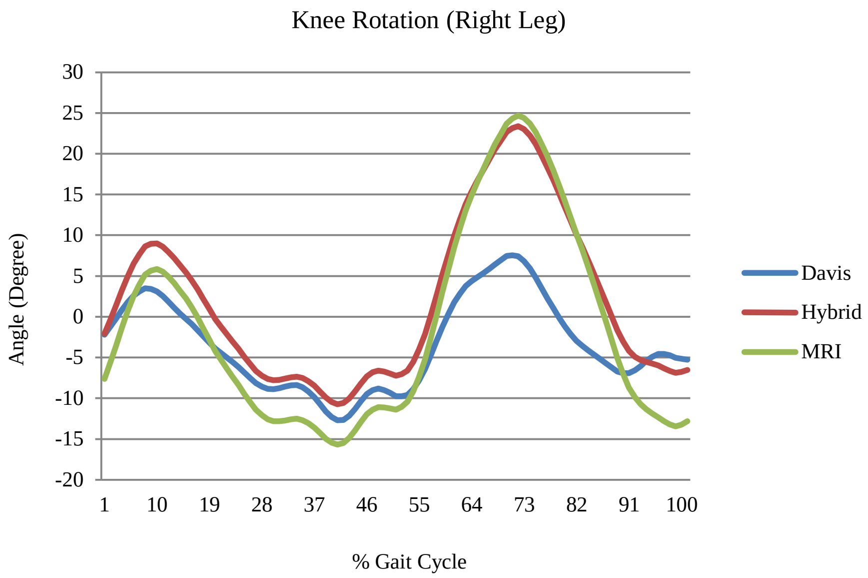
a)



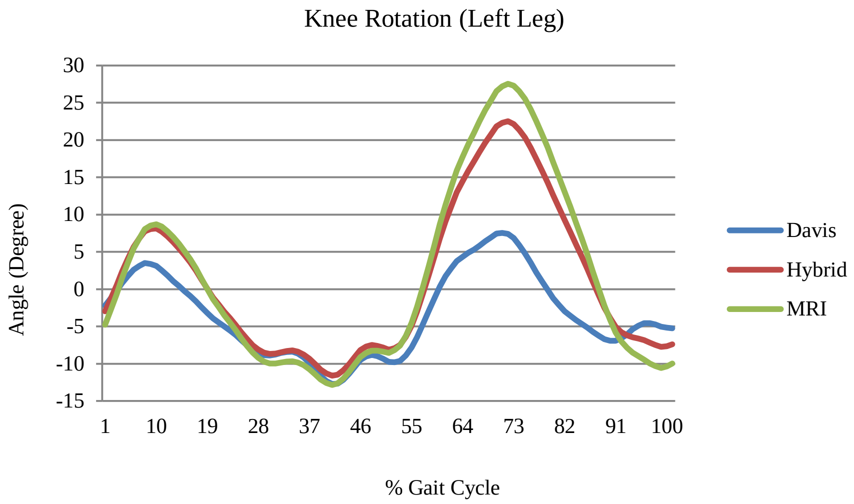
b)

Figure 32 Smoothed Right/Left Knee Valgus

For the right leg the results of Davis method are more reasonable than hybrid and MRI methods. For the left leg results of MRI and Davis methods are reasonable. 15 degree of Knee Valgus in MRI data (for right leg) cannot be true (Figure 32).



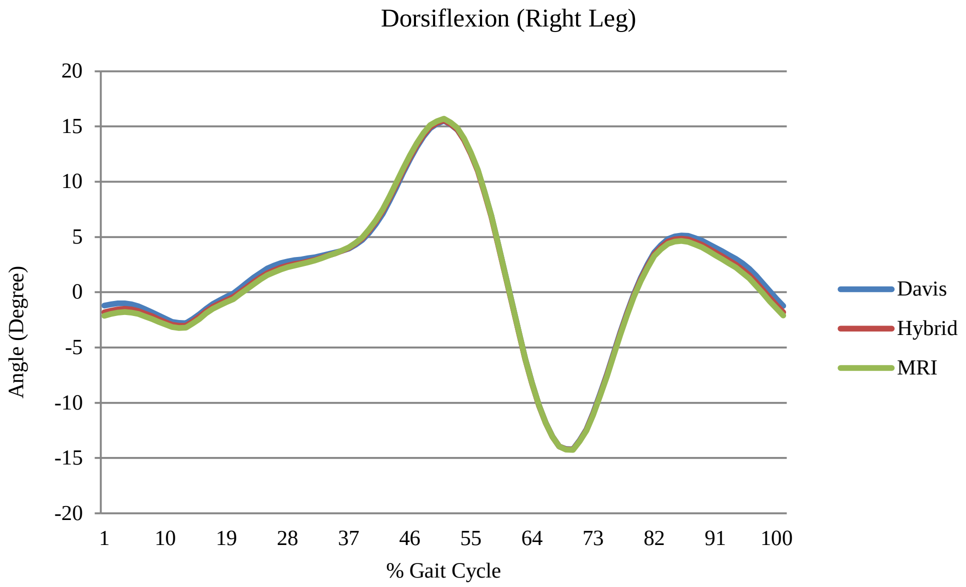
a)



b)

Figure 33 Smoothed Right/Left Knee Rotation.

Like data of the knee valgus, for both right and left legs the results of Davis method are reasonable than hybrid and MRI methods. 20 degree of knee rotation in MRI data cannot be true (Figure 33).



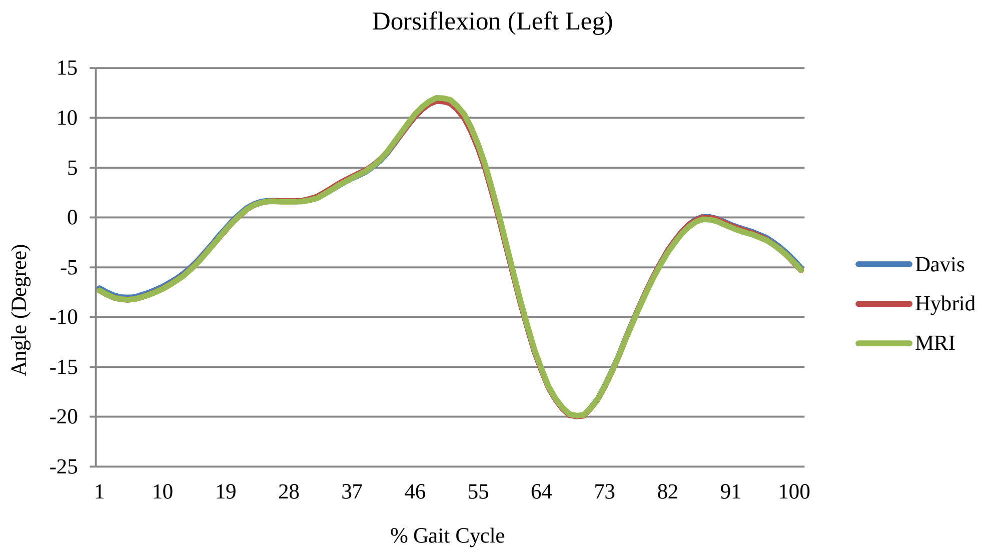
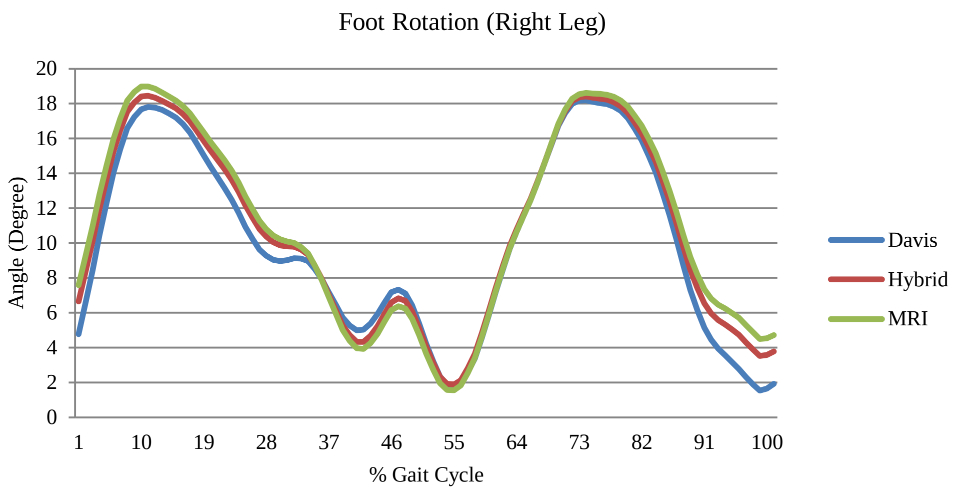
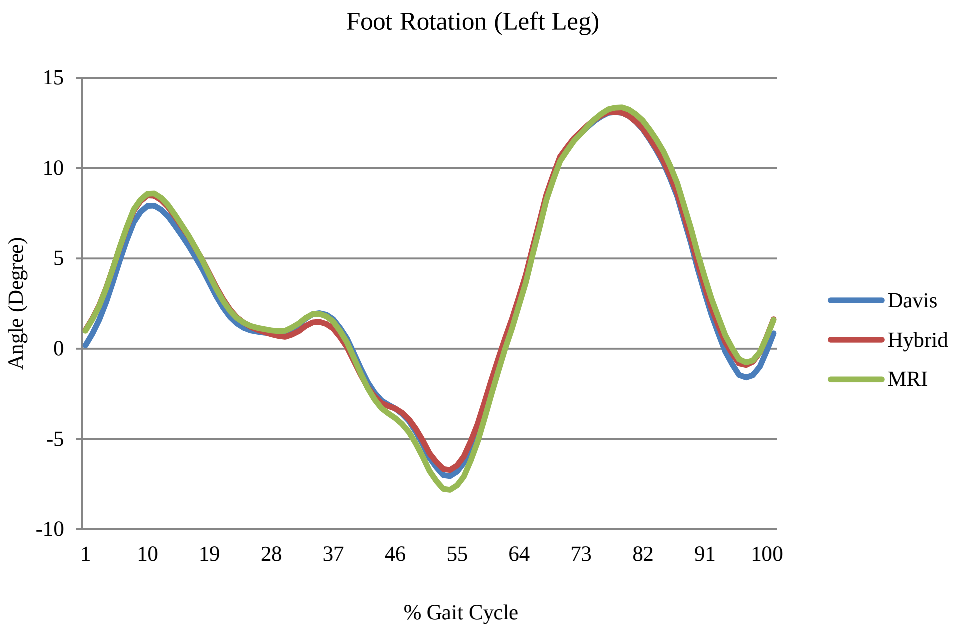


Figure 34 Smoothed Right/Left Dorsiflexion.

There is not much difference between the dorsiflexion data (Figure 34) of three methods; all of the results for the right and left legs are very close to each other.



a)



b)

Figure 35 Smoothed Right/Left foot rotation.

Like dorsiflexion data, the results of the foot rotation in all three methods are from very close to each other (Figure 35).

5.2 CONCLUSION

In the above data the kinematic results of lower extremities (hip, knee and foot) by using hip joint center obtained using MRI, Davis and combination of methods are presented. The combined method composed of Davis and Bell methods was analyzed and compared with results of Davis and MRI methods. In this thesis a new method of HJC estimating was not proposed. The purpose of analyzing a combined method is to evaluate the aspects of the methods and compare with Davis method and MRI data. In Chapter 3 of this thesis a procedure for matching the coordinate system constructed using MRI data to the coordinate system of gait experiments was proposed.

Anthropometric methods generally are presented for healthy young and adults of both sex (men and women) not for elderly people and children. In this study, all subjects were young and healthy male. Since the combined method composed of two separate anthropometric methods (Davis and Bell), the results could be applied for young healthy female subjects as well.

The results of hip joint in all three methods are close to each other; however, the results of Davis method for knee valgus and knee rotation are reasonable than the other two analyzed methods.

5.3 SUMMARY, DISCUSSION AND FUTURE WORKS

This thesis deals with comparing different hip joint enter estimation methods with MRI method (assumed as the golden standard) and a procedure of matching MRI data into METU gait analysis protocol was explained. The study is composed of three main parts: First part involves introduction of different hip joint center estimation methods together with their advantages and disadvantages. In the second part comparison of different widely used hip joint center estimation methods with the hip joint centers estimated by MRI are presented. In this part the details of matching MRI data to METU gait analysis system was proposed and the procedure of creating pelvis coordinate system was explained in details. The last part consists of presenting the kinematic results of MRI data, Davis method and a combination of Davis and Bell methods.

According to data, none of the presented methods could estimate the location of hip joint center accurately in all three directions. The analyzed, combination of methods composed of Bell (1990) and Davis (1991) methods. In this method, in posterior (x) direction, the method presented by Bell predicting HJC in 19.30% of PW has selected. In distal direction Davis method and for medial direction Bell's method are preferred.

In posterior direction Bell method could estimate with difference less than 2 mm (S.D. 0.08 mm) with respect to MRI data. In distal direction method presented by Davis could estimate hip joint center in less than 15 mm (S.D. 10 mm) with respect to MRI data. Finally in medial direction Bell method could estimate with difference about 6 mm (S.D. 0.26 mm) with respect to MRI data.

All subjects have similar results so the presented results demonstrate improvement by applying combined method. As an example, the joint kinematic data of subject AB (Chapter 5) are presented according to three methods (current Davis method, the MRI method and analyzed combination of methods).

All presented anthropometric methods are applicable for healthy young and adult of both sexes (not for pathologic, children and elderly people). The results in this thesis show that in posterior and medial directions, the anthropometric methods could predict hip joint center more accurate than functional methods; however, considering all three directions, the results of functional methods are better than anthropometric methods. Actually the results of functional methods depend on many factors such as the applied algorithm, soft tissue artifact, the type and range of movements, marker cluster design and duration and combination of movements. Of all the above reasons the main limitations which could affect the results of functional methods in this study are the type of the movement and marker cluster.

This study could be extended for healthy female or children or elderly subjects (applying both functional and anthropometric methods) as well as young and elderly pathologic subjects (applying only functional methods) of both sexes. Generated Matlab® code by Kafalı (2007) yields kinematic gait results only, the implementation of kinetic data to Matlab® code (joint moment and power) of gait experiment could be as future works. For better investigation of functional methods, it is recommended to change marker cluster design and adapt new algorithms of joint center estimation. In addition, applying different or combination of movement type during experiment for healthy subjects could increase the reliability of these methods too.

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APPENDIX A: FUNCTIONAL METHODS OF HIP JOINT ENTER ESTIMATION

B-1 ITERATIVE SPHERE FITTING ALGORITHM

Iterative sphere fitting algorithm (SFA) presented by Hicks and Richards in 2005. In the research, performances of three sphere fitting algorithms compared using computer generated data and employed the method that yielded the most satisfactory results for clinical assessment. This method, which is an iterative sphere fitting algorithm utilizing Newton's method, was adapted to Kiss protocol for assessment of its performance in METU Gait Analysis System by Kafali in 2007.

Main objective of the employed sphere fitting algorithm is to minimize the following expression:

$$\varepsilon_i = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2 + (z_i - z_c)^2} - r \qquad \text{(B-1)}$$

In the above equation (x_i, y_i, z_i) are coordinates of any point in the given data set, (x_c, y_c, z_c) are coordinates of the sphere center, r is sphere radius and ε_i is the error function.

The algorithm computes sphere radius and sphere center coordinates by assuming the error associated with each data point is zero. Then, for a set containing n data points, the system of equations becomes:

$$\begin{aligned} \varepsilon_1 &= \sqrt{(x_1 - x_k)^2 + (y_1 - y_k)^2 + (z_1 - z_k)^2} - r_k \\ \varepsilon_2 &= \sqrt{(x_2 - x_k)^2 + (y_2 - y_k)^2 + (z_2 - z_k)^2} - r_k \\ &\vdots \\ \varepsilon_n &= \sqrt{(x_n - x_k)^2 + (y_n - y_k)^2 + (z_n - z_k)^2} - r_k \end{aligned} \qquad \text{(B-2)}$$

where k represents number of iterations.

The calculation procedure starts at $k = 0$ with initial guesses for (x_k, y_k, z_k) and r_k. In each iteration, improvement vector δ_k is calculated to obtain new estimates of sphere center and radius as follows:

$$\begin{bmatrix} x_{k+1} \\ y_{k+1} \\ z_{k+1} \\ r_{k+1} \end{bmatrix} = \begin{bmatrix} x_k \\ y_k \\ z_k \\ r_k \end{bmatrix} + \delta_k \quad \text{(B-3)}$$

The improvement vector δ_k is calculated from the equation

$$J_k \delta_k = -F_k \quad \text{(B-4)}$$

where F_k is the error function and J_k is the Jacobian of this function, with expressions given as

$$F_k = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} = \begin{bmatrix} \sqrt{(x_1 - x_k)^2 + (y_1 - y_k)^2 + (z_1 - z_k)^2} - r_k \\ \sqrt{(x_2 - x_k)^2 + (y_2 - y_k)^2 + (z_2 - z_k)^2} - r_k \\ \vdots \\ \sqrt{(x_n - x_k)^2 + (y_n - y_k)^2 + (z_n - z_k)^2} - r_k \end{bmatrix} \quad \text{(B-5)}$$

$$J_k = \begin{bmatrix} \frac{\partial \varepsilon_1}{\partial x_k} & \frac{\partial \varepsilon_1}{\partial y_k} & \frac{\partial \varepsilon_1}{\partial z_k} & \frac{\partial \varepsilon_1}{\partial r_k} \\ \frac{\partial \varepsilon_2}{\partial x_k} & \frac{\partial \varepsilon_2}{\partial y_k} & \frac{\partial \varepsilon_2}{\partial z_k} & \frac{\partial \varepsilon_2}{\partial r_k} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial \varepsilon_n}{\partial x_k} & \frac{\partial \varepsilon_n}{\partial y_k} & \frac{\partial \varepsilon_n}{\partial z_k} & \frac{\partial \varepsilon_n}{\partial r_k} \end{bmatrix} = \begin{bmatrix} -\frac{(x_1 - x_k)}{r_k} & -\frac{(y_1 - y_k)}{r_k} & -\frac{(z_1 - z_k)}{r_k} & -1 \\ -\frac{(x_2 - x_k)}{r_k} & -\frac{(y_2 - y_k)}{r_k} & -\frac{(z_2 - z_k)}{r_k} & -1 \\ \vdots & \vdots & \vdots & \vdots \\ -\frac{(x_n - x_k)}{r_k} & -\frac{(y_n - y_k)}{r_k} & -\frac{(z_2 - z_k)}{r_k} & -1 \end{bmatrix} \quad \text{(B-6)}$$

Hicks and Richards (2005) utilized knee joint center coordinates expressed in pelvis reference frame as the input data to the algorithm. Initial guess for hip joint center coordinates were obtained from the least squares algorithm presented in their study.

In adaptation of this method to Kiss system, reconstructed knee joint center coordinates were used to compute the hip joint center. As an initial guess, hip joint center coordinates computed from the predictive method (Davis et al., 1991) were used and iterations were performed until difference between two successive iterations was less than 10^{-3} mm, as presented by Hicks and Richards (2005).

The algorithm calculates hip joint center coordinates localized to pelvis frame, from knee and hip joint center (as initial guess for algorithm) coordinates which are also expressed in pelvis frame. Therefore, global coordinates of these points were first converted into pelvis frame coordinates by use of the following relations:

$\bar{r}_{HJC,p}{}^{(p)} = \hat{C}^{(G,p)T}(\bar{r}_{HJC}{}^{(G)} - \bar{r}_{PLVS}{}^{(G)})$ …………………………………. (B-7)

In the above equation, $\bar{r}_{HJC,p}{}^{(p)}$, is knee and hip joint center coordinate vectors, expressed in pelvis reference frame.

Hip joint center coordinates obtained from the sphere fitting algorithm were then converted into global coordinates as:

$\bar{r}_{HJC}{}^{(G)} = \bar{r}_{PLVS}{}^{(G)} + \hat{C}^{(G,p)}\bar{r}_{HJC,p}{}^{(p)}$ …………………………………….. (B-8)

where $\bar{r}_{HJC,p}{}^{(p)}$ is the new hip joint center coordinate vector localized to pelvis frame, calculated using the sphere fitting algorithm.

B-2 LINEAR LEAST SQUARE ALGORITHM

Second functional hip joint center estimation method adapted to Kiss protocol is an algorithm proposed by Piazza et al. (2004).

Defining hip joint center coordinates in pelvis and thigh anatomical frames as (x, y, z) and (u, v, w); and the 4×4 homogeneous transformation matrix between thigh and pelvis frames as

(which represents squared error if the hip is a spherical joint)

$$T_{P/T} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ t_x & r_{xx} & r_{xy} & r_{xz} \\ t_y & r_{yx} & r_{yy} & r_{yz} \\ t_z & r_{zx} & r_{zy} & r_{zz} \end{bmatrix} \text{……………………………………………………….. (B-9)}$$

The above transformation can be used to find the coordinates of the thigh-frame hip joint center in the pelvis frame, permitting the square of the distance between the hip fixed joint center and the thigh-fixed joint center for the ith sample of motion data to be expressed as:

$$\varepsilon_i{}^2 = (t_x + r_{xx}u + r_{xy}v + r_{xz}w - x)^2 + (t_y + r_{yx}u + r_{yy}v + r_{yz}w - y)^2 + (t_z + r_{zx}u + r_{zy}v + r_{zz}w - z)^2 \text{ ………………………………………… (B-10)}$$

For a set consisting of *n* points, the total squared error is then:

$$SE = \sum_{i=1}^{n} \varepsilon_i{}^2 \text{ ………………………………………………………… (B-11)}$$

Total squared error is minimized by differentiating the above equation with respect to the unknown variables x, y, z, u, v, and w, and setting them equal to zero. The obtained set of linear equations is in the form

$$AX - b = 0 \qquad \text{(B-12)}$$

where $X^T = [x\ y\ z\ u\ v\ w]$ and A is the symmetric matrix:

$$A = \begin{bmatrix} n & 0 & 0 & -\sum r_{xx} & -\sum r_{xy} & -\sum r_{xz} \\ 0 & n & 0 & -\sum r_{yx} & -\sum r_{yy} & -\sum r_{yz} \\ 0 & 0 & n & -\sum r_{zx} & -\sum r_{zy} & -\sum r_{zz} \\ -\sum r_{xx} & -\sum r_{xy} & -\sum r_{xz} & a_{44} & a_{45} & a_{46} \\ -\sum r_{xz} & -\sum r_{yy} & -\sum r_{yz} & a_{54} & a_{55} & a_{56} \\ -\sum r_{zx} & -\sum r_{zy} & -\sum r_{zz} & a_{64} & a_{65} & a_{66} \end{bmatrix} \qquad \text{(B-13)}$$

with

$$a_{44} = \sum {r_{xx}}^2 + {r_{yx}}^2 + {r_{zx}}^2$$

$$a_{45} = a_{54} = \sum r_{xy}\, r_{xx} + \sum r_{yy}\, r_{yx} + \sum r_{zy}\, r_{zx}$$

$$a_{46} = a_{64} = \sum r_{xz}\, r_{xx} + \sum r_{yz}\, r_{yx} + \sum r_{zz}\, r_{zx}$$

$$a_{55} = \sum {r_{xy}}^2 + \sum {r_{yy}}^2 + \sum {r_{zy}}^2$$

$$a_{65} = a_{56} = \sum r_{xz}\, r_{xy} + \sum r_{yz}\, r_{yy} + \sum r_{zz}\, r_{zy}$$

$$a_{66} = \sum {r_{xz}}^2 + \sum {r_{yz}}^2 + \sum {r_{zz}}^2$$

$$b = \begin{bmatrix} \sum t_x \\ \sum t_y \\ \sum t_z \\ -(\sum t_x\, r_{xx} + \sum t_y\, r_{yx} + \sum t_z\, r_{zx}) \\ -(\sum t_x r_{xy} + \sum t_y r_{yy} + \sum t_y r_{zy}) \\ -(\sum t_x r_{xz} + \sum t_y r_{yz} + \sum t_z r_{zz}) \end{bmatrix} \text{.................................. (B-14)}$$

Hip joint center coordinates are then calculated by solving for X, where the first three elements are hip joint center coordinates localized to pelvis reference frame, and the remaining elements are the coordinates of hip joint center localized to thigh reference frame.

In adaptation of this method to Kiss protocol, homogeneous transformation matrix between pelvis and thigh anatomical frames were employed in the algorithm. As previously, global coordinates of computed hip joint center were determined via the equation

$$\bar{r}_{HJC}{}^{(G)} = \bar{r}_{PLVS}{}^{(G)} + \hat{C}^{(G,p)}\bar{r}_{HJC,p}{}^{(p)} \text{..(B-15)}$$

where $\bar{r}_{HJC,p}{}^{(p)}$ is the coordinate vector of hip joint center in pelvis frame, calculated from the linear least squares algorithm.

GLOSSARY OF TERMS

Abduction	Movement away from midline of the body in frontal plane
Adduction	Movement towards midline of the body in frontal plane
Anterior	Towards the front of the body
ASIS	Anterior Superior Iliac Spine; most anterior superior point of ilium (upper part of hip bone)
Cadence	Number of steps per minute
Distal	Away from center of the body or point of attachment of limb to the body
Dorsiflexion	Flexion of the foot in an upward direction
Extension	Movement at a joint that increases the angle between adjacent segments
External Rotation	Rotation away from midline of the body in transverse plane
Femoral epicondyle	Bony structure on the outer sides of knee
Femur	Long bone of the upper leg
Flexion	Movement at a joint that decreases the angle between adjacent segments
Frontal (Coronal) Plane	Plane that divides human body into front and back portions
Gait	Manner or style of human walking
Gait Analysis	Scientific description of human walking

Gait Cycle	Series of movements between two successive gait events of the same foot
Greater Trochanter	Bony area on the lateral and proximal end of femur
Heel Strike	Gait event denoting first contact of foot with the ground
Inferior	Away from the head or towards the lower part of the body
Internal Rotation	Rotation towards midline of the body in transverse plane
Lateral	Away from the midline; towards outer side of the body
Malleolus (pl. Malleoli)	Rounded projection on both sides of the ankle joint
Medial	Towards the center/midline of the body
Metatarsal	Any bone of foot between ankle and toes
Pelvis	Bony structure of hip area
Plantar Flexion	Downward movement of foot in sagittal plane
Posterior	Towards the back of the body
Proximal	Towards center of the body or point of attachment of limb to the body
Sacrum	Triangular bone structure composed of five fused vertebrae at the base of the spine
Sagittal Plane	Plane that divides human body into right and left portions
Shank	Part of human leg between knee and ankle

Stance	Period of gait where foot is in contact with the ground
Step	Distance between successive heel strikes of opposite feet
Stereophotogrammetry	Motion capture
Stride Length	Distance between two successive heel strikes of the foot
Superior	Towards the head or upper part of the body
Swing	Period of gait where foot is not in contact with the ground
Thigh	Part of human leg between hip and knee
Tibia	Larger bone of the lower human leg
Toe-Off	Gait event denoting removal of foot from the ground
Transverse Plane	Plane that divides human body into upper and lower portions
Valgus	Turning outward away from midline of the body in frontal plane
Varus	Turning inward towards midline of the body in frontal plane