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In Vivo Verification of Different Hip Joint Center Estimation Methods in Gait Analysis For Healthy Subjects

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Abstract: 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. Inaccuracies in estimation of hip joint center are shown to propagate errors in kinematic and kinetic calculations of lower extremities.

In literature there are different methods to determine HJC. Although invasive methods like radiography, computed tomography and magnetic resonance imaging 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. 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 (<u>Ki</u>nematic <u>S</u>upport <u>S</u>ystem in English, *<u>K</u>as <u>İ</u>skelet <u>S</u>istemi* 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. METU gait analysis system, utilizes one of the predictive methods, the Davis method to determine hip joint center location. This method is very straightforward and easy to use. However, in this method, the determination of the positions of anatomical landmarks depends 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.

This study 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 method in posterior direction, Davis method in distal direction and Bell's method in medial direction was analyzed and the results were criticized for the accuracy.

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1. Introduction

Estimating the subject specific location of hip joint center (HJC) is required in biomechanical and clinical gait analysis to calculate kinematic and kinetic quantities. Both hip and knee joint angles and moments are reported to be affected by HJC mislocation. It is reported that a 30 mm HJC anterior mislocation reduces flexion/extension component of the hip joint moment about 22%, a 30 mm lateral HJC mislocation reduces abduction/adduction component about 15% and a 30 mm posterior HJC mislocation produced a delay of the flexion-to-extension timing in the order of 25% of the stride duration (Stagni, 2000).

HJC may be estimated by using invasive or non-invasive methods. Although invasive methods like x-ray or magnetic resonance imaging results in accurate estimations, these methods are time consuming and may be hazardous for the subject. Therefore, in clinical and most biomechanical gait analysis applications various non-invasive methods are preferred. Non-invasive methods may further be classified as predictive and functional methods. In predictive methods, based on previous studies regression equations using anthropometric measurements of subjects, the location of hip joint center is estimated. In functional methods, based on the relative motion of thigh with respect to the pelvis, the center of rotation, which is the HJC is determined.

In this study, seven predictive methods (method presented by Tylkowski (1982), which modified twice by Bell in 1989 and 1990, Davis method presented in 1991, two methods presented by Seidel in 1995 and a method by Harrington in 2007) and two functional methods (Linear Least Squares Algorithm proposed by Piazza in 2004 and Iterative Sphere Fitting Algorithm, presented by Hicks and Richards in 2005) of HJC locating were compared with the HJC obtained by sphere fit to the three dimensional computer model of head of the femur obtained by magnetic resonance imaging for eight young, healthy male volunteers.

2. Materials and Methods

2.1. Subjects and Equipment

A group of eight healthy young male subjects all having a normal bony framework and with anthropometric measurements shown in Table 1 (age 22-29; body mass 64-85 kg; Stature 1.70-1.79 m) voluntarily contributed to the study. The experiments were performed under the approval of the Ethics Committee of Middle East Technical University (Ankara- Turkey).

Table 1. Anthropometric measurement of the subjects.

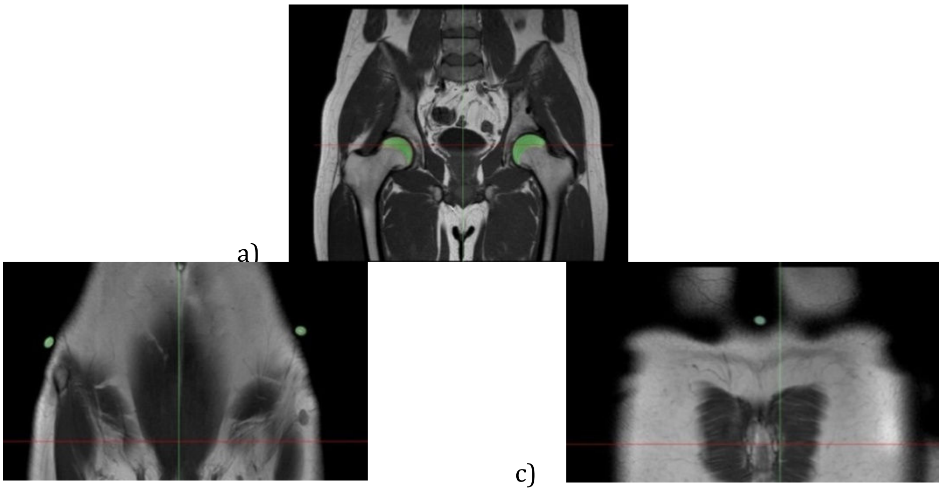
Subject	ASIS-ASIS (mm)	RLL (mm)	LLL (mm)	RKW (mm)	LKW (mm)	RAW (mm)	LAW (mm)	Weight (kg)	Stature (m)	Age (Years)
AVE.	257.12	920	920	93	93	54	54	75.63	1.73	24.5
RLL: Right Leg Length, LLL=Left Leg Length, RKW=Right Knee Width, LKW=Left Knee Width, RAW=Right Ankle Width, LAW=Left Ankle Width.										

Gait analysis data is acquired using the in-house METU-Kiss system (Shafiq *et al,* 2001). Modified Helen Hayes marker set was applied. Kinematic data acquisition was performed with six charge-coupled device (CCD) cameras (Ikegami Electronics, Inc., Maywood, NJ, USA) positioned around the laboratory, with a sampling frequency of 50 Hz. Force measurement unit consists of two force plates (type 4060 HT, Bertec Corporation, Columbus, OH, USA) which are embedded in walkway for acquisition of ground reaction forces and moments, two amplifiers and a data acquisition card. A computer code with a graphical user interface was developed in Matlab® (Version 7.1.0.246 R14, the MathWorks Inc., MA, USA) for re-generation of the joint kinematics calculations (Kafalı, 2007). MRI of the volunteers were acquired by Philips, Achieva, 1.5 T, (Netherlands) equipment in Atatürk Research and Educational Hospital (Ankara Turkey) with T1 Weighted, Coronal (T1W) and 2 mm of slice thickness by experienced radiologists.

2.2. Experiment Procedure

For the gait analysis, prior to each gait experiment the cameras were linearized and calibrated. Two sets of experiments were performed, stance (static) and walking (dynamic) trails. Stance trial requires 19 and walking trial requires 13 markers to be attached on the lower extremity of the subject. Stance trial calibrates anatomical landmarks and based on these, reference frames were constructed such that their planes approximate anatomical planes of segments. Utilization of the anatomical frames in joint angle, moment and power calculations yielded results in clinically meaningful coordinates (e.g. flexion-extension, abduction adduction etc.). Construction of anatomical frames entails determination of knee and ankle joint centers, which were located in static trial by use of anatomical landmark calibration methods. For each segment, technical and anatomical reference frames were constructed from static shot data. Transformation between these two frames was assumed to remain constant at all times, since segments were considered as rigid. During dynamic trial only technical reference frames could be constructed from recorded data. Anatomical reference frames at each time instant could then be obtained in dynamic trial, from technical frames constructed using dynamic trial data, and the constant transformation constructed during static trial between anatomical and technical frames (Güler, 1998; Kentel, 2002).

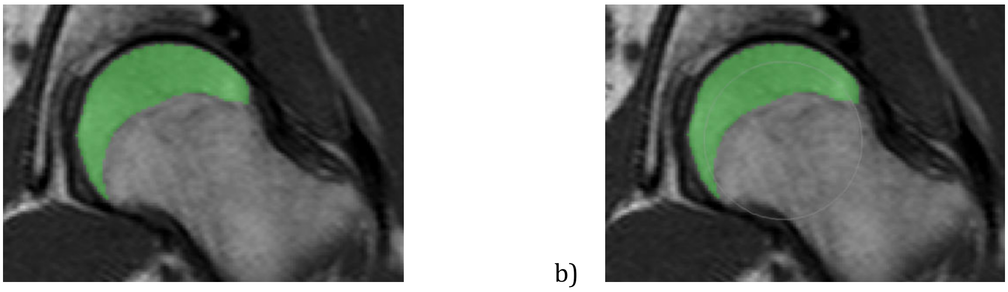
The MRI data of the subjects were acquired on the same day they had the gait analysis. The location of sacrum, right and left ASIS markers used in gait analysis were marked using fish oil tablets which are visible in MRI. MRI data includes pelvis and heads of both femurs (Figure 1). For comparing the results of MRI and gait laboratory data, the generated pelvis coordinate system in both needs to be identical. MR images were imported to 3Dslicer 3.6 program (the Slicer community). The three gait markers and pubic symphysis were marked by four small spheres. The heads of the two femurs were fitted by two spheres and these entities were saved as a CAD file (Figure 1) and this file was opened by Solidworks® (Version 2009, Dassault Systèmes SolidWorks Corp.) program.



a) b) c)

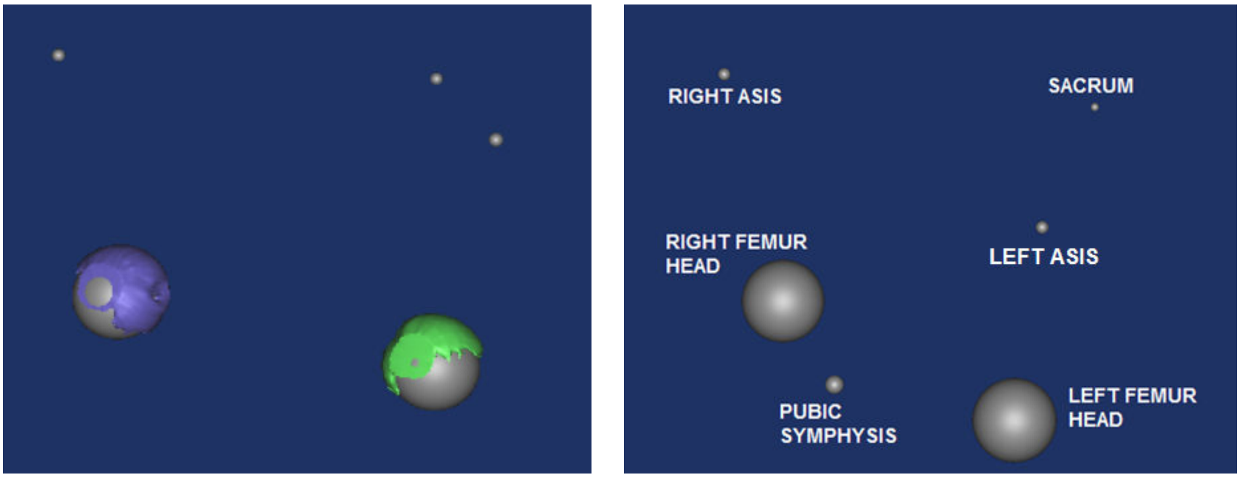
Figure 1. Segmentation process on femur heads (a), fish oil tablet on ASISs (b) and sacrum (c) in 3Dslicer 3.6 program (data belongs to subject AB).

Head of the femur is spheroidal rather than spherical. During daily activities (because of loading) head of the femur changes its shape (Peterson and Bronzino, 2008) and the magnitude of the load influences the loading pattern on the femoral head. The boundary of femoral head (the boundary which head of the femur is close to spherical shape) was selected as presented in Figure 2.



a) b)

Figure 2. The head of the femur boundary selected for sphere fitting (a) and fitted sphere (b).



a) b)

Figure 3. The spheres fitted on MRI data (a) and the CAD file which consists of spheres fitted on the subparts (b) (data belongs to subject AB).

Three-dimensional model of ASIS and sacrum markers used during gait analysis were created in Solidworks® and assembled to the CAD file to create the pelvis coordinate system used in gait analysis (Figure 3). Pelvis coordinate system and the coordinate system defined by Seidel in 1995 (Figure 4) were created accordingly.

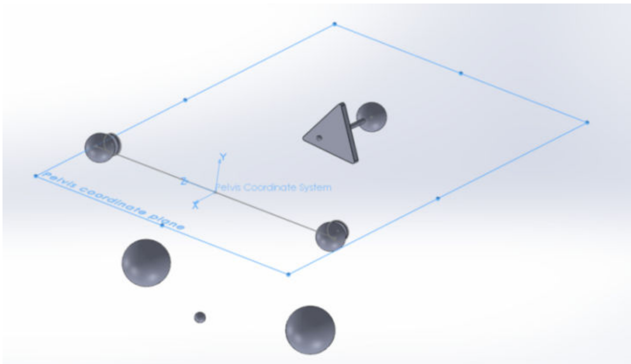


Figure 3. Pelvis coordinate system, which defined by sacrum and ASIS markers (data belongs to subject AB).

2.3. Predictive methods

Seven widely used predictive methods were selected (Table 2). First method introduced by Tylkowski in 1982 and modified twice by Bell *et al.* in 1989 and 1990. They presented the location of hip joint center in percent of pelvis width (PW, also known as ASIS-ASIS distance) in three anatomical directions. Second is Davis method presented in 1991. This method is introduced at Newington Children's Hospital in 1981 through the radiographic examination of 25 hip studies. Third and fourth methods are presented by Seidel *et al.* (1995). In the first version Seidel located HJC in all directions as percent of ASIS-ASIS distance (%PW), and in the second version, he presented the 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). Fifth method was proposed by Harrington *et al.* (2007) who analyzed methods proposed by Davis (1991), Bell (1990) and recommendations for OrthoTrak, Motion Analysis Corp., (CA, USA) and proposed another method.

†Table 2 presents the predictive methods compared in this study.

† $\beta = 18°$, $\theta = 28.4°$, $x_{dis} = 0.1288, L_{leg} - 48.56$, $C = 0.115L_{leg} - 15.3$,
L_{leg} : Leg length (mm), r_{marker}: Marker radius, PW: Pelvis width, PH: Pelvis height, PD: Pelvis depth

Table 2. Predictive methods

METHOD	Posterior direction- x	Medial direction- z	Distal direction-y
Tylkowski (1982)	21% PW	11% PW	12% PW
Bell et al. (1989)	22% PW	14% PW	30% PW
Bell et al. (1990)	19.30% PW	14.1% PW	30.4% PW
Davis. (1991)	$[-x_{dis} - r_{marker}]\cos\beta + C\cos\theta\sin\beta$	$[-x_{dis} - r_{marker}]\sin\beta - C\cos\theta\cos\beta$	$-\sigma[C\sin\theta - \frac{d_{ASIS}}{2}]$
Seidel 1995	24% PW	14% PW	30% PW
Seidel 1995	34% PD	14% PW	79%PH
Harrington et al. (2007)	$-0.24PD - 9.9$	$0.33PW + 7.3$	$-0.30PW - 10.9$

The coordinate system applied in all above predictive methods is pelvis coordinate system except the methods by Seidel (1995). Seidel assumed that the frontal plane passes from ASISs and pubic symphysis, x direction is perpendicular to the frontal plane, z direction is along ASIS-ASIS line and y direction is perpendicular to x and z direction, forming right handed orthogonal coordinate system (Figure 4).

2.4. Functional methods

These methods rather than using predictive equations based on previous measurements, try to locate the rotation center of the femurs with respect to the pelvis based on the relative motion of femurs with respect to the pelvis. Two functional methods were evaluated. First method is Linear Least Squares Algorithm (LSA) proposed by Piazza et al. (2004). This method is based on minimization of a cost function using a linear least squares approach. The second one is Iterative Sphere Fitting Algorithm (SFA) presented by Hicks and Richards (2005). The algorithm (utilizing Newton's method) computes sphere radius and sphere center coordinates by assuming the error associated with each data point is zero. Marker cluster design, applied algorithm, type, range and duration of motion are factors that affect the results of functional methods.

3. Results

Location of HJC was predicted by utilizing four predictive and two functional methods and results obtained were compared with the predictions done by MRI.

3.1. Method of Tylkowski and its modification by Bell

Table 3 presents the HJC location of eight subjects obtained from MRI results, which are presented as percent of ASIS-ASIS distance (% PW).

Table 3. HJC of eight subjects obtained by MRI presented in percent of ASIS-ASIS distance.

Subject	PW (mm)	Posterior direction- x (% PW)	Medial direction- z (% PW)	Distal direction- y (% PW)
AB	251	19.75	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.	-	2.93	2.02	3.54

Assuming that results by Bell in 1990 are better than Bell (1989) and Tylkowski (1982), its differences by MRI method (Table 3) show that in posterior and medial directions this method yields better results (where the difference is 0.67% of PW in posterior and 1.98% of PW in medial direction) than the distal direction where the difference is 13.16% of PW.

3.1. Davis (1991) method

The average results of Davis formulation and its difference with respect to MRI data for our eight subjects are shown in the Table 4. Average error is less in posterior and medial directions.

Table 4. Average difference and S.D. of results of Davis method 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		6.28		6.33		13.74
S.D.		4.49		3.50		10.18

3.3. Methods of Seidel

Seidel (1995) defined a different coordinate system than pelvis coordinate system. He referred the frontal plane as the plane passing through both ASISs and the pubic symphysis (Figure 4). The coordinate system was defined with its origin at the midpoint of ASISs in which y-axis is in mediolateral (positive medial-defined by ASISs), z-axis in superodistal (positive distal), and x-axis in anteroposterior (positive posterior) directions.

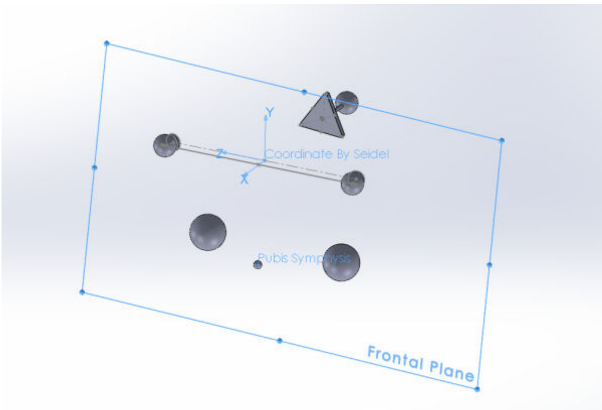


Figure 4. The coordinate system defined by Seidel (1995).

Results of this study according to Seidel first method are expressed in Table 5. Differences between the MRI results and Seidel reveal that the method yields better results in posterior and medial directions (average error of 5.76% in posterior and 2.19% in medial direction of ASIS distance) than the distal direction (average error of 13.74%). Like the method proposed by Bell (1990) the method presented by Seidel yields acceptable and accurate results in medial and posterior directions, but in distal direction the prediction is far from the center predicted by MRI. 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 6).

Table 5. Difference between the MRI results and hip joint center in all directions as percent of ASIS-ASIS distance presented by Seidel

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	16.29	17.16	43.38
SI	246	13.30	18.92	43.21
MT	267	20.03	16.21	42.51
MC	275	18.63	16.08	43.56
Total Average of MRI data	-	18.24	16.19	43.74
Seidel 1995	-	24	14	30
Magnitude of Difference	-	5.76	2.19	13.74
S.D. of MRI data	-	6.52	3.98	8.70

Table 6. Average 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
Results by Seidel 1995	-	79	-	34
Difference	-	4.93	-	7.39
S.D.	-	9.48	-	4.95

In this method, the results of HJC location in distal direction are better than his first method with difference of 4.93% of PH (which difference varies from 4.24 mm to 6.52 mm). For posterior direction, the difference is 7.39%, which is larger than the methods by Davis (1991) and Bell (1990).

3.2. Method by Harrington

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 7).

Table 7. Average results of Harrington (2007) formulation in eight subjects and average difference with respect to MRI results.

	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	

3.3. Linear Least Square Algorithm (LSA)

Results of HJC location estimated by least square algorithm and its differences with respect to MRI results in three directions are expressed in Table 8.

Table 8. Average Hip Joint Center of subjects using Least Squares Algorithm (LSA) and the difference with respect to MRI data

-	-	Posterior direction-x (mm)		Medial direction-z (mm)		Distal direction-y (mm)	
Subject	Leg	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

Average difference value in posterior and medial directions is less than 10 mm, so this method can be used in these directions.

3.4. Iterative Sphere Fitting Algorithm (SFA) presented by Hicks and Richards (2005)

Results of HJC location estimated by sphere fit algorithm and its differences with respect to MRI results in three directions are expressed in Table 9.

Table 9. 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

Average error of this method in medial and distal directions is more than 20 mm.

4. Discussion and Conclusions

Differences of each method in three directions with respect to MRI data are shown in Table 10. All methods have large error in distal (y) direction except Davis and Piazza method where the differences from MRI predictions are less than 20 mm.

Table 10. Evaluation of presented methods (differences are with respect to MRI data and are in mm).

Method	Average of Differences in x (posterior) direction	Average of Differences in y (distal) direction	Average of Differences in z (medial) direction
Bell (1990)	1.75	34.31	5.17
Davis (1991)	6.17	13.76	6.33
Seidel (1995), first method	14.81	35.33	5.63
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

As long as pelvis depth in the subject cannot be measured in gait analysis laboratories, the method by Harrington is not practical in the clinical gait analysis system except for research purposes. SFA by Hicks and Richards has larger error in distal and medial directions (more than 20 mm) so according to Stagni et al. (2000) the results of gait analysis data will contain a relatively large error, which is unacceptable.

By comparison of all anthropometric and functional methods, it is concluded that none of these methods could predict HJC accurately in all three directions as pointed out by Bell (1990), so to achieve optimal kinematic and kinetic results in gait analysis systems a hybrid method could be used. The recommended hybrid method is as below:

a- For posterior direction the method presented by Bell (1990) yields best results (19.30% of PW).
b- For medial direction first method of Seidel (1995) which predicts hip joint center as 14% of PW medially, is recommended.
c- For distal direction Davis (1991) or LSA by Piazza (2004) method could be used. For clinical analyses, because of simplicity Davis method is recommended.

The results in Table 10 reveal that in posterior and medial directions anthropometric methods are 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, from functional methods, LSA by Piazza and from anthropometric methods Davis method is preferred to apply and between these two methods, functional method (LSA by Piazza) has least differences.

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