Hip Joint Centre Localization: Evaluation of Formal Methods and Effects on Joint Kinematics

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Abstract. Accurate methods of hip joint centre (HJC) localization are necessary in gait analysis. It was shown that current methods could involve large mislocation errors, what affect both kinematics and kinetics. The purpose of present study was to compare three different HJC localization methods: predictive methods, functional calibration methods, and medical imaging analysis technique, as well as to assess of its effect on joint kinematic variables during gait on population of three able-bodied subjects. Significant deviations were observed for HJC determined with predictive method compared to ultrasound technique (44 ± 7 mm), resulted in errors propagating into calculated joint angles (mean 2.7°). While lower deviations observed for functional method comparing to ultrasound technique (mean 23 ± 6 mm) results in negligible joint angle differences (mean 0.6°). Therefore, functional methods are highly recommended in the absence of imaging technique.

Keywords: hip joint centre, gait analysis, sphere fitting, freehand ultrasound.

1 Introduction

An accurate localization of hip joint centre (HJC) is of interest across wide range of applications, especially in lower limb movement analysis and computer aided surgical intervention to determine alignment of lower limb anatomical axes [1,2,3]. In gait analysis, location of HJC affects both kinematic and kinetic variables [4,5]. HJC is assumed to be ball-and-socket joint with rotation centre is coincident with centre of femur head. Therefore there are three different approach to HJC localization: predictive methods, functional calibration methods, and medical image techniques in recent years [4,6].

The most widely used methods in gait analysis are predictive methods based on anthropometric estimation. There are available several regression equation [7,8,9,10] based on empirical relation between position of palpable pelvis landmarks and HJC. Currently, the most widely applied is Davis equation [7], which estimates position of HJC from positions of pelvis markers and lower limb length. This regression equitation was developed on the basis of planar X-rays of very limited and specific population of living subjects (25 subjects), which obviously

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lead to inaccurate results [11,6]. Although, later equations [8,9], stemmed from medical images from wider population, with proven greater accuracy [6,11] were proposed, mainly Davis equation is implemented in commercial software.

The next type are functional methods, which determine centre of rotation from pelvis and thigh marker positions during calibration movements. For this purpose, there are two different approaches, sphere fitting techniques and transformation techniques. In first approach, centre and radius of sphere as optimized to segment marker trajectories during movement of femur relative to pelvis [1,8,12,13,14]. In transformation techniques, pelvis and thigh local coordinate systems are defined and joint centre is approximated as fixed point in both local coordinate systems [1,15,16]. Both approaches were compared and evaluated, simulation studies gave better results for transformation techniques [1] and an in-vitro analysis [17], while sphere fitting techniques performed better in in-vivo study (cadaver study [18] and living subject analysis using medical imaging [6]). Although, choice of appropriate approach among functional methods, seems to remain unresolved, in general functional methods perform better than predictive methods [6,11].

Medical imaging techniques, such as MRI [9], bi-plane X-rays [11,19,20] and three dimensional ultrasound [6,21], are used rather as a gold standard measurement tools in the evaluation of the other methods, than in clinical gait analysis.

Many different predictive and functional methods were compared and evaluated using medical imaging data in previous papers [1,6,11,17,18,20,22]. It has been shown, that hip joint centre position discrepancy alter both kinematics and kinetics [4,5]. In these studies, different HJC position errors from specific range were introduced to kinematic model to calculate corresponding kinematic and kinetic variables. Analysed errors were not actual HJC mislocation obtained for the same population as kinematic description. Direct effect of HJC location estimated using different methods on kinematic and kinetic variables have not been investigated.

The purpose of the present study was to compare three different HJC localization methods: regression equation, functional method and ultrasound technique, as well as assessment of direct effect of HJC mislocation on joint kinematic variables during gait.

2 Materials and Methods

Three able-bodied subjects (two female and one male) without a walking disability were analyzed (A: female, height: 167 cm, BMI: 26.89 kg/m^2, age: 33 years, B: male, height: 188 cm, BMI: 24.62 kg/m^2, age: 25 years, C: female, height: 158 cm, BMI: 18.43 kg/m^2, age: 26 years). Subjects were on purpose diverse in terms of body mass index. Participants underwent three different anatomical calibration procedure: 1) palpation of external bone landmarks of lower limb 2) functional calibration movements 3) ultrasound examination and gait analysis. Hip joint centers localization were estimated using three different methods: freehand ultrasound measurement (medical image technique), least squared sphere fitting (functional method) and Davis equation [6] (predictive method).

2.1 Free-Hand Ultrasound Measurement

The ultrasound measuring system, described and validated in previous paper [2,23], consisting of ultrasound probe EchoBlaster 128 (Telemed, Lithuania) and infrared optical tracking system – Polaris (NDI, Canada) was applied (Fig. 1). 2D ultrasound images are transformed to 3D coordinates of each pixels through a calibrated ultrasound probe equipped with active markers. Thereby the system measures spatial geometry of bones and soft tissues with a high accuracy.

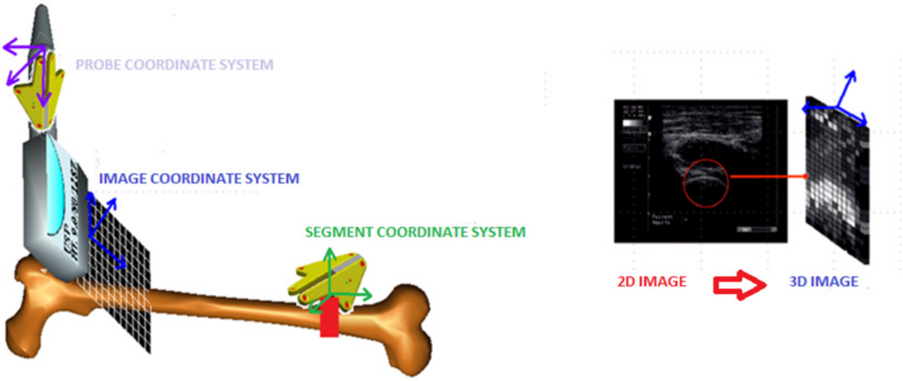

Fig. 1. Principle of free-hand ultrasound system

Six scans of femur head of right lower limb for different probe orientations were recorded for each subject. Hip joint centre position was estimated using a simplified method – as the centre of circle matched to femur head contour averaged over four selected scans. Position of HJC was determined relative to the marker cluster placed on distal part of thigh.

2.2 Functional Method

The functional calibration movement was arc movement consisting of a hip flexion, a half circumduction and a extension to the neutral position. Each subject was asked to perform series of calibration movement at a self-selected speed, while motion capture system (Optotrak Certus, NDI, Canada) tracked position and orientation of clusters of non-collinear active markers (Optotrak Smart Marker Rigid Body, NDI, Canada) placed on the pelvis and distal part of thigh.

Algebraic sphere fitting method together with some of transformation techniques were applied to estimate centre of hip rotation from collected data. First, the origin of thigh cluster coordinate system was transformed into a coordinate system of pelvis cluster.

It was assumed, that origin of femoral segment cluster move on the surface of sphere with specific radius around common centre (pelvic centre of rotation).

Centre of rotation was estimated using algebraic sphere approach, called Kasa-Delonge method [1], which in this case minimizes the following sum:

$$f_{algebraic}(c_p, r_1, ..., r_n) = \sum_{i=1}^{n} (\| p_{ci} - c_p \|^2 - r^2)^2 \quad (1)$$

where c_p is the centre and r is the radius of sphere, p_{ci} is the origin of femoral cluster in pelvis coordinate system in the time frames $i = 1, ..., n$. This minimization task has simply close solution (opposed to geometric sphere fitting method, where minimization is a non-linear problem solved iteratively).

The centre of rotation and radius of sphere were calculated from coordinates of the thigh cluster origin during functional movement using a Matlab script [24]. Root-mean-square error (RMS error) and normalized RMS (radius RMS error divided by mean radius) for radius were calculated. HJC position in pelvic cluster coordinate system (c_t) was transformed into thigh cluster coordinate system using:

$$c_t = \frac{1}{n} \sum_{i=1}^{n} c_{ti} = \frac{1}{n} \sum_{i=1}^{n} T_{t_i}^{-1} T_{p_i} c_p{}', \quad (2)$$

where c_{ti} is instantaneous HJC position in the thigh cluster coordinate system, T_{ti} is global transformation of thigh cluster coordinate system , T_{p_i} is is global transformation of pelvis cluster coordinate system in $i = 1, ...n$ time frames and c_p is sphere centre in pelvis coordinate system.

2.3 Predictive Method

Position of hip joint centre was estimated using Davis method [7] as widely used predictive method in gait analysis. HJC position was calculated on the basis of positions of sacrum, anterior superior iliac spine right and left (ASIS right and left) and lower limb length. Anatomical landmark locations were measured as in 2.4. HJC was defined in pelvic anatomical coordinate system and recalculated to femur cluster coordinate system for neutral, standing position.

2.4 Gait Analysis

Right lower limb motion during gait was tracked using motion capture system (Optotrak Certus, NDI, Canada) consisted of single position sensor with three cameras (Fig. 2). Data acquisition, joint kinematic calculations, the gait visualization and data recording were performed with a software developed by the author [25].

Four clusters of three non-collinear active markers (Optotrak Smart Marker Rigid Body, NDI, Canada) on rigid plates were placed on each segment (pelvis, thigh, shank and foot) enables tracking of each lower limb segment independently. Fully anatomical gait analysis protocol based on anatomical joint coordinate system specified by twelve palpable anatomical bony landmarks of right lower limb and HJC was used (according to ISB recommendation [26]).

Anatomical landmarks were indicated using a navigated pointer (equipped with markers)[25], while its positions were registered in the reference of corresponding cluster. Positions of thus defined virtual markers were calculated on the basis of an actual clusters position and anatomical calibration data.

Relative orientation of adjacent lower limb segments was defined as the relative orientation of anatomical coordinate systems determined using Cardan's angular convention [27]. The three Cardan angles were used to describe the hip and knee joint action of a flexion/extension, an adduction/abduction, and an internal/external rotation.

Subjects walked barefoot with low speed. Three gait cycles for each subjects were selected from the series of recorded cycles. Three different HJC relative position, obtained using predictive, functional and ultrasound methods, were introduce to kinematic model together with calculated trajectories of other anatomical landmarks. The results are the three kinematic descriptions of gait (corresponding to three hip joint centre localization methods) for the same set of gait cycles. Data was processed, including filtering of marker trajectories with 4th order low-pass Butterworth filter (cut-off 6Hz) and joint angle normalisation to 100 point per cycle using Matlab.

Fig. 2. Gait analysis system

For visual comparison of three kinematic description of gait, joint angle curves (mean over 3 cycles) were plotted for each subject. Differences between two pairs of angles (angles for Davis HJC estimation and functional method compared to the kinematic variables for ultrasound measurement) were averaged over gait cycle for each subject and presented in box plots.

3 Results

In free-hand ultrasound method, position of HJC was estimated as a mean circle centre matched to four femur head contours from different scans. Spread of circle centres around average differs among subjects, RMS errors were from 4,9 mm (subject C), 6.1 mm (subject B), to even 13.7 mm (subject A).

Thigh cluster trajectory (consisted of at least 645 data points for subject A) were fitted to sphere with relatively high accuracy (Fig. 3, Fig. 4, Fig. 5). Calculated RMS errors for radius were from 3 mm (subject C) to 6 mm (subject A). Range of motion (ROM) during functional calibration was substantial.

There were differences between HJC positions estimated with three procedures (Tab. 1) observed especially in a transverse plane. Generally HJC position estimated by functional method is more comparable to free-hand measurement (mean linear distance 23 ± 6mm) than predictive method (mean linear distance 44 ± 7 mm). The greatest discrepancies were observed in subject A.

Observed HJC location differences altered values of kinematic variables (Figures 6, 7). Kinematics obtained for functional HJC are more comparable to ultrasound HJC than those for predictive method. The impact of the HJC position on kinematic parameters vary across the subjects.The greatest discrepancies were observed for flexion/extension angles in subject A and for ab/adduction angles in subject C. HJC mislocations did not almost neither affect knee nor hip rotation.

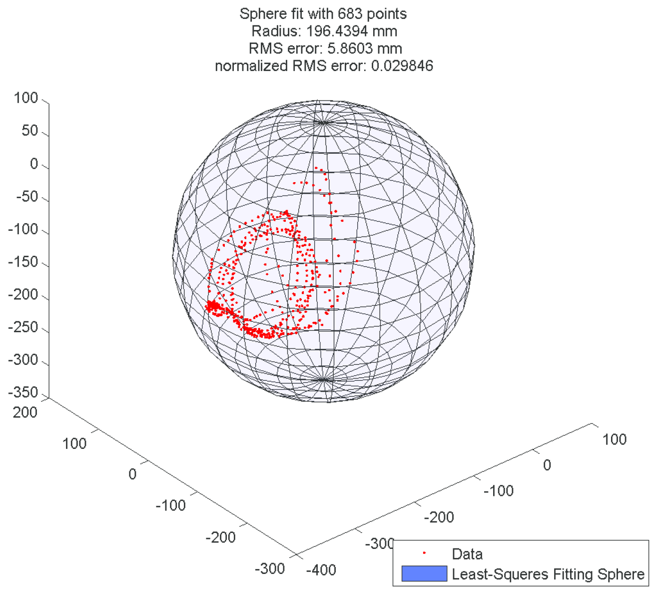

Fig. 3. Sphere fitted to thigh cluster trajectory of subject A

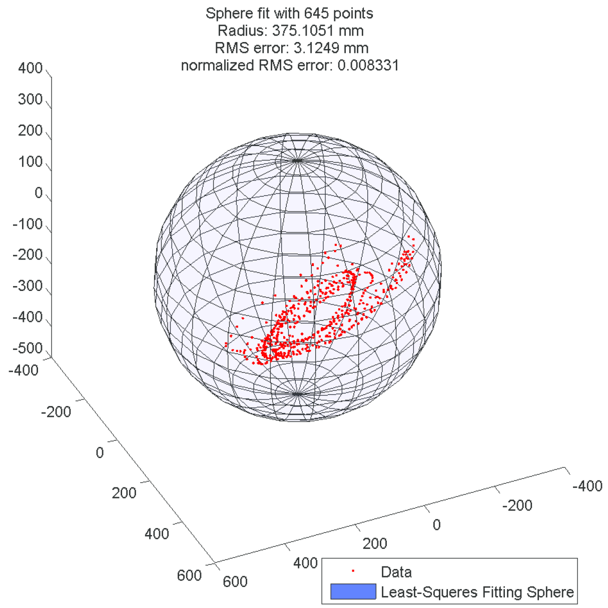

Fig. 4. Sphere fitted to thigh cluster trajectory of subject B

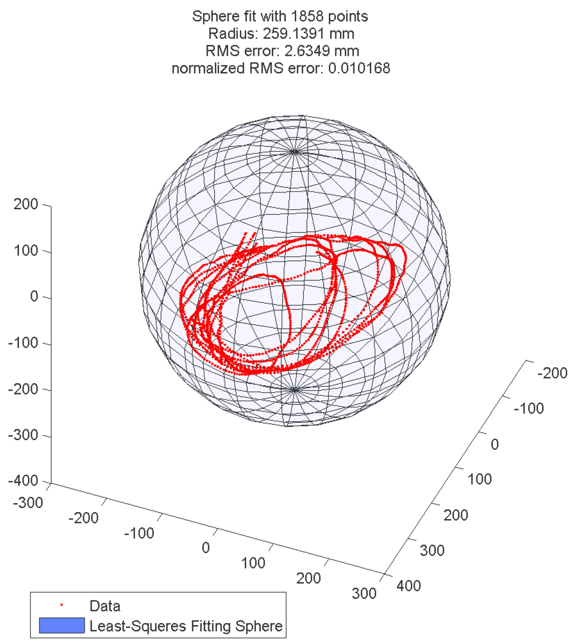

Fig. 5. Sphere fitted to thigh cluster trajectory of subject C

Table 1. Linear distance and distance in each plane between hip joint centre positions indicated by three different methods (regression equation, free-hand ultrasound measurement, functional calibration); coordinates differences should be interpreted as follows: in x anterior, y superior, z lateral in the femur coordinate system (defined by lateral and medial epicondyles indicated with pointer and femur head indicated by ultrasound measurement)

	Subject	ΔX	ΔY	ΔZ	Δ [mm]
Davis equation vs. ultrasound measurement	A	-41	28	-4	50
	B	33	-1	14	36
	C	17	-3	41	44
				mean	43 ± 7
Sphere fitting vs. ultrasound measurement	A	2	24	16	29
	B	19	4	9	21
	C	9	-4	-15	18
				mean	23 ± 6
Sphere fitting vs. Davis equation	A	-43	-4	-21	48
	B	14	-4	6	16
	C	8	0	55	56
				mean	40 ± 21

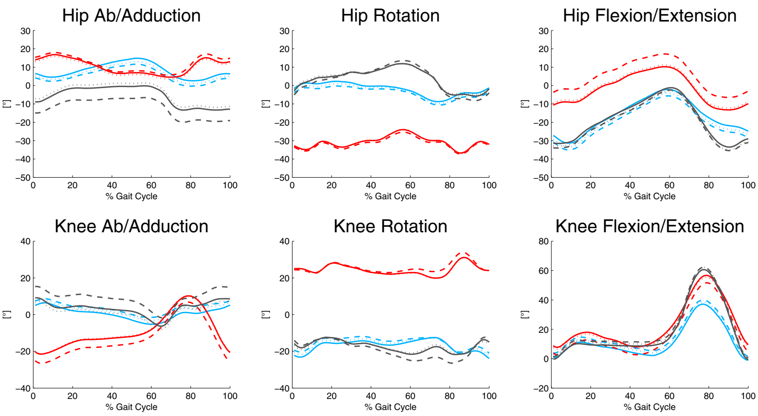

Fig. 6. Kinematic variables as calculated for three HJC localization procedures: Davis equation(dashed line), functional method (doted line) and ultrasound procedure (solid line), averaged across three cycles for three subject: A(red), B(blue), C (grey)

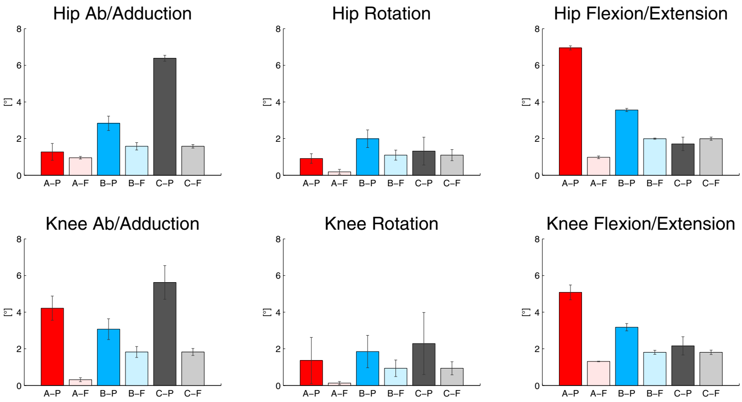

Fig. 7. Differences between joint angles calculated for three HJC localization procedures averaged over gait cycle for each subject A(red), B(blue), C (grey). Kinematic variables corresponding to Davis predictive (symbol P, darker bar) and functional (symbol F, lighter bar) methods were compared to those for ultrasound procedure

4 Discussion

Three procedures were applied: ultrasound-based method, functional (sphere fitting algorithm) and predictive (Davis equation) to estimate HJC localizations of three subject very diverse in terms of physique. Although applied ultrasound measurement system enables measurement of bone and tissue geometry with the high accuracy, applied HJC estimation method (by circle matching to the contour) is simplified and hence its accuracy is limited (as shown in 3). This ultrasound method should be improved in the future, especially that high accuracy of such method is achievable as it was shown in previous paper [6]. However it is reasonable to assume, that estimated HJC is inside femur head. The disadvantage of using this method in gait analysis is a need for additional examination using further equipment (properly calibrated ultrasound probe). Furthermore, interpretation of ultrasound images is difficult, and the bone contour is not always distinguishable from the surrounding tissues. Despite these limitations, the high reproducibility of ultrasound musculoskeletal geometry measurement is possible.

Davis equation is based on data from limited and specific population, it depends on accuracy of pelvis anatomical landmarks palpation. It is reported to performed badly [6,11]. Also in this study, results significantly differ from the other, which also reveals in kinematic data. The main advantage of using this method in the gait analysis is no need for any additional anthropometric measurements, equipment or performance of calibration movement.

Algebraic sphere fitting method together with some of transformation techniques were implemented to estimate HJC on the basis of current marker set (marker clusters). Functional methods are independent from anatomical calibration accuracy, however it is prone to soft tissue artifacts, especially during extensive calibration movement. In previous paper was shown, that functional methods outperformed predictive methods [6,4]. Implemented sphere fitting algorithm estimated centers of rotation with relatively low radius RMS errors. Functional procedure and ultrasound method gave similar results. Functional methods do not require any additional measurements or equipment. Calibration movements are not time consuming, however can not be performed by patients with reduced hip mobility.

HJC mislocations, obviously propagate to hip and knee kinematic variables. HJC mislocations almost din not affect observed knee and hip rotation, what is consistent with anatomical coordinate frames definitions. HJC mislocation in mediolateral direction affects add/abduction angles, while discrepancy in anterior-posterior direction influences flexion/extension angles.

Deviation in HJC location using functional and ultrasound methods (mean 23±6 mm) can be overestimated due to limited ultrasound method (reported deviations are smaler [21,6,17,11]). Despite the deviation in HJC location, the corresponding kinematic data sets are similar, while kinematic data for Davis method differ considerably.

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