The Accuracy of the Use of Functional Hip Motions on Localization of the Center of the Hip

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Abstract

Background: The hip joint is generally considered a ball-and-socket joint, the center of which is used as an anatomic landmark in functional analyses and by surgical navigation systems. The location of the hip center has been estimated using functional techniques using various limb motions. However, it is not clear which specific motions best predicted the functional center.

Purpose: This study aims to compare the predicted functional center of the hip evaluated from multiplanar circumduction and star motions, and to compare this functional center with the geometric center.

Methods: Eight hips in four fresh-frozen cadavers were used and verified as morphologically normal in CT scans. Three-dimensional motion of each lower limb was recorded using arrays of reflective markers rigidly attached to the femur and pelvis. Each hip was manipulated to produce circumduction or star motion, i.e., abduction–adduction and flexion

extension. The hip was then dissected and the bearing surface traced with a probe, from which a best-fit sphere was calculated. The functional center was calculated from the motion data and compared to the geometric technique.

Results: There was no difference between the functional hip center predicted by circumduction or star motions, although this was offset from the geometric hip center by up to 14 mm. For all except two hips, the functional center was less than 6 mm from the geometric hip in each anatomic direction. Test–retest differences were smaller for circumduction than for star motions.

Conclusions: Estimation of the hip center based on motion of the femur relative to the pelvis could localize the geometric center of the joint within 14 mm and circumduction motions were more repeatable.

Clinical Relevance: Many surgical navigation systems make use of the functional hip center as a landmark for alignment or reconstruction. Errors associated with this would have a very minor influence in lower limb alignment, e.g., for knee reconstruction, but could affect proximal femoral geometry relevant to hip reconstruction.

Keywords hip center · functional center · estimation · accuracy · surgical navigation

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Introduction

The hip is generally considered a ball-and-socket joint in which rotations occur about a fixed point. The centroid of this joint is used in functional analyses of the hip such as the center of joint rotations in motion studies [1] and muscle moment arms in determining muscle activity [2, 3]; as a reference location for determining femoral offset and anteversion, and lower limb alignment in navigated reconstructive surgery, especially in total knee arthroplasty [4]; and as a landmark for determining and applying the hip contact force in inverse dynamics and finite element analyses [5, 6].

More recently, femoroacetabular impingement (FAI) has been identified as a potential major cause of osteoarthritis [7]. FAI results from a deformity in the femoral head–neck

Fig. 1. Prescribed motions used to determine the functional hip center. A complete trial consisted of five cycles of circumduction of the femur (*left*), flexion/extension (*right, top*), and adduction (*right, bottom*). Flexion/extension and adduction trials were combined to create a star motion

junction or acetabular overcoverage, and may result in repeated abnormal contact between femoral- and acetabular-bearing surfaces. Determining the functional center of the hip and relative motions between the femur and acetabulum are therefore prerequisites to investigating impingement conditions in vivo.

Various methods have been used to estimate the center of the hip joint, including MRI-based simulations [8], regression equations using bone landmark geometry [9] and functional methods [10–12]. Image-based determination of the hip center requires expensive medical imaging as well as registration of the location to the patient or anatomic coordinate system for subject assessment. Regression equations, also known as the predictive technique, are often used in motion analysis studies, but are less accurate than functional methods in estimating the joint center [11, 13]. More commonly, the hip center is determined using a functional technique, whereby the center of rotation is estimated from motion capture data of the femur moving relative to the pelvis [10–13]. These techniques typically use reflective markers mounted on the skin and are prone to soft tissue artifacts which reduce the accuracy of measurement and are challenging to overcome [14, 15]. Studies using mechanical linkages, in which the center of rotation is known a priori, have shown that circumduction motions give the most accurate estimate of the joint center [16] especially if the range of motion is at least 30° [16, 17]. Various mathematical techniques may be used to reduce the marker motion to a single center of rotation and a review of these techniques and their sensitivity to experimental noise was reported by Ehrig et al. [18]. Transformation techniques do not require an iterative optimization routine and are considered more accurate and much less sensitive to noise compared to sphere fitting techniques [12, 16, 18].

The accuracy of estimating the functional hip joint center due to various mathematical [12, 14, 16] or experimental [11, 13] techniques has been widely discussed. However, few have compared the predicted functional center with the

geometric center [12, 13], or the sensitivity of this to the prescribed motion. The correspondence between the functional and geometric centers is an important assumption underlying some surgical navigation systems which use the functional center as a navigation landmark. Furthermore, changes to this correspondence may be important in studying hip pathology such as FAI. The purpose of this in vitro study was therefore to compare the geometric center with the functional center of rotation calculated from two different nonplanar hip motions as well as with a regression technique in nonpathologic hips.

Materials and Methods

Eight hips from four fresh-frozen cadavers were used in this study. Each specimen was thawed for 1 day prior to testing. CT scans of the specimens were performed to confirm that the alpha angle was less than 50° [19] and to exclude any pathologic joint, ensuring that all joints were normal. Reflective marker arrays from a commercially available surgical navigation system (Brainlab, Inc., IL, USA) were used for optical three-dimensional tracking of the motion segments. An array was mounted to the mid-diaphysis of the femur using two 4-mm threaded Steinmann pins. A second array was similarly mounted to the iliac crest. Skin markers were applied to the abdomen, thigh, and shank to define landmarks used for anatomic coordinate systems.

Tracking of the femur and pelvis arrays was performed with a five-camera Vicon motion tracking system (Vicon Motion Systems, Oxford, UK) during manipulation of the lower limb. Before motion trials began, static trials were performed with the specimen supine and on the side. Skin markers from the right and left anterior superior iliac spines and the sacrum were used to define the pelvic anatomic coordinate system; skin markers from the medial and lateral epicondyles were used to define the femoral anatomic coordinate system (Fig. 1). The origins of the pelvic and femoral coordinate systems were defined as the spherical centers of the acetabular and femoral bearing surfaces, respectively, as described below. From these static “snapshots”, a transformation from the anatomic to marker array coordinate system was defined for the pelvis and femur, and was assumed constant. These transformations were used to express results in an anatomic coordinate system [20].

Motion trials were performed with the specimen on the side, braced by a wooden frame, so that gravity minimized distraction forces. A trial consisted of five cycles each of circumduction, flexion extension, and adduction; each trial was performed three times. The leg was manipulated to achieve a large hip range of motion without distracting the hip. Rotation angles were confirmed during data analysis to be at least 25° flexion, 5° extension, 20° abduction, and 10° adduction. Marker coordinate data were collected at 50 Hz. Data from the flexion extension and adduction trials were combined to simulate a star motion. After the motion trials, the hip joint was carefully dissected so as not to disturb the rigidly mounted marker arrays. Once the hip was dislocated, a probe with reflective tracking markers was used to trace

the acetabular- and femoral-bearing surfaces. To calculate the geometric centers of the femoral head and acetabulum, the trace data were first transformed into the coordinate system of the respective tracking arrays. The geometric center was then calculated using a Gauss–Newton least-squares sphere fit and used as the origin of the respective anatomic coordinate system as described above.

For each of the three trials of circumduction and star motions, the functional center was determined over the full trial using the symmetric center of rotation method [18]. This method assumes that the rotation of the joint occurs about a common point in the global coordinate system and does not require an iterative solution technique. The joint center location was calculated in Matlab (The MathWorks Inc, MA, USA) using a least-squares algorithm (mldivide). This determined a center of rotation in the coordinate system of the pelvis and femur tracking arrays which was then transformed to the respective anatomic coordinate system using the transformations described above.

The center of the hip was also estimated using the regression technique of Davis et al. [9] Before each trial, the leg length was measured as the distance from the anterior superior iliac spine (ASIS) to the ipsilateral medial malleolus, as well as the inter-ASIS distance for use in the regression equations. The location was then transformed to the pelvic anatomic coordinate system.

To measure the accuracy in estimating the hip center using either the functional or regression technique, their respective joint center coordinates were expressed in an anatomic coordinate system which had the geometric hip center as its origin, i.e., (0,0,0) for the anterior, superior, and medial coordinates, respectively. Thus, any deviation from the origin by either of the functional or regression-derived centers of rotation is a direct measure of their accuracy in estimating the geometric center.

For femoral data, a nonparametric paired sample Wilcoxon test was performed to test differences between

Fig. 2. Predicted functional hip center in the sagittal plane of the femoral coordinate system from circumduction (*solid*) and star (*open*) motions. *Lines* connect results from the same specimen. The origin (0,0) represents the geometric center; units are in millimeters

Fig. 3. Predicted functional hip center in the coronal plane of the femoral coordinate system. See Fig. 2 for more details

circumduction and star motions in each coordinate direction; the functional center of each motion type was similarly tested vs. zero in each direction to test the accuracy of predicting the geometric center. For acetabular data, differences in the functional and regression-predicted centers were first tested with a repeated measures Kruskal–Wallis test, followed by Wilcoxon tests to examine specific differences between methods. All tests were performed independently for each coordinate dimension (anterior, superior, and medial).

Results

The functional hip center was typically found to be distal and lateral to the geometric center of the femur for both circumduction and star motions (Figs. 2 and 3). The median functional center was found to lie within 6 mm of the geometric center of the femoral head in each coordinate axis with the exception of two specimens (1R and 4L). There was no significant difference in location of the functional hip center as determined from circumduction compared to star motions in each direction for the femur (Table 1, $p > 0.26$) or acetabulum (Table 2, $p > 0.3$). The pelvic tracking tool was bumped during dissection of one specimen (1L) and results are therefore not available for the acetabulum of this specimen.

The hip joint center predicted by the regression analysis was anterior and inferior to the geometric center ($p < 0.018$); in the medial–lateral direction, results did not show an obvious trend but varied from the geometric center by up to 13 mm (Table 3). The three-dimensional distance between the predicted center and the geometric center ranged from 13.5 to 25 mm, and showed least agreement in the anterior direction. There was also a significant difference between the hip center predicted by regression and by the functional method in the anterior and superior directions ($p < 0.028$).

Test–retest differences were calculated from the maximum and minimum value in each direction for three trials.

Table 1 Functional center of the hip relative to the geometric center of the femoral head; mean (millimeters) of three trials, positive values in directions indicated

Specimen	Side	Circumduction			Star		
		Anterior	Superior	Medial	Anterior	Superior	Medial
1	L	−1.1	−1.1	0.0	0.1	−1.0	0.5
	R	8.3	−5.0	−3.9	3.6	−6.4	−4.8
2	L	0.8	−2.8	−2.1	−0.3	−2.4	−1.1
	R	2.8	−0.2	−0.2	1.1	−0.9	−0.4
3	L	1.7	−2.3	−0.8	1.4	−1.9	−1.7
	R	3.1	−0.1	−5.9	0.9	0.2	−5.3
4	L	11.5	−2.1	−4.6	13.7	−1.1	−3.2
	R	2.0	−2.1	−0.7	2.8	−2.3	0.9
Compare to geometric	<i>p</i>	0.025	0.012	0.012	0.025	0.017	0.069

Mean test–retest differences were 2.2 mm for circumduction and up to 3.7 mm for star motions. Star motion showed larger variability in test–retest differences with up to 13 mm indicating that this method is less precise.

Discussion

The purpose of this in vitro study was to compare the effects of using two different motions on estimating the hip joint center, as well as with the regression technique. The circumduction and star motions used here were within the range of those used to estimate the hip joint center during surgery [21]. This study found that the mean functional hip center predicted by either circumduction or star motions are equivalent, and that in most cases these can provide an estimate of the geometric hip center within 6 mm in each coordinate dimension. The hip center predicted by regression was much less accurate than the functional methods, which differed from the geometric center by 13–25 mm in at least one of the coordinate dimensions.

Differences in functional and geometric centers may have been due to measurement error, either tracking the individual bone segments or the sphere trace; however, the magnitudes of the differences were in the range reported by previous studies [12, 22]. Errors in the estimate of the geometric center may contribute to the overall differences between functional and geometric centers, although the

uncertainty in the sphere center location was less than 0.2 mm. Additionally, differences may have occurred due to the hip joint. It was assumed that the joint was spherical with a single, constant center of rotation. Laxity in the joint or a noncongruent joint due to undiagnosed pathology may cause the hip motion to violate this assumption. Two specimens (1R and 4L) exhibited a large offset between functional and geometric centers regardless of motion type. This offset resulted in more motion of the femoral geometric center relative to the acetabular center (not shown) for these specimens, suggesting that at small scales the hip joint does not follow the expected motion for a spherical ball and socket joint. It has been suggested that the hip joint is a conchoid [23] which may explain deviations from the expected pure rotations.

This study used rigid marker arrays to track the motion of the pelvis and femur segments. Although this is appropriate in surgical navigation systems, it is not practical for functional studies of motion. Use of skin markers in such studies would introduce errors due to skin motion [15, 24] and decreases the accuracy of the joint center estimates, especially where the soft tissue layer is thick [14]. As such, the current study must be taken in context and evaluation of how these locations may differ is underway.

Leardini et al. estimated the geometric center from roentgen stereophotogrammetric analysis and showed that functional methods estimated the spherical center with an accuracy of 13 mm compared to 25–30 mm for regression

Table 2 Functional center of the hip in acetabular coordinate system; mean (millimeters) of three trials

Specimen	Side	Circumduction			Star		
		Anterior	Superior	Medial	Anterior	Superior	Medial
1	R	6.2	8.2	−6.1	2.7	4.8	−8.3
2	L	3.3	−5.2	−11.1	2.4	−5.6	−9.5
	R	3.4	−0.2	−1.9	2.0	−1.2	−2.6
3	L	2.5	2.0	−1.4	1.6	1.9	−2.1
	R	2.2	2.1	−3.1	−1.0	2.4	−3.5
4	L	−1.1	−0.1	−1.6	0.3	1.3	0.2
	R	−0.8	−0.5	−2.4	0.2	−0.3	0.3
Compare to geometric	<i>p</i>	0.063	0.735	0.018	0.063	0.5	0.063

Table 3 Center of the hip predicted by regression technique

Specimen	Side	Anterior	Superior	Medial
1	R	3.4	−0.1	−13.1
2	L	21.2	−10.9	8.0
	R	17.5	−7.1	12.6
3	L	13.2	−6.6	−3.9
	R	16.1	−9.7	8.0
4	L	13.3	−1.8	−4.2
	R	13.7	−15.8	0.9

methods, similar to the magnitudes in the current study [13]. However, the functional method tended to predict a hip center that was posterior (4.3 mm) and lateral (3.6 mm) compared to the RSA-measured hip center, rather than lateral and inferior in the current study. Similarly, the functional center estimated the geometric center within 13 mm when the latter was located using an ultrasound technique [11]. Lopomo et al. determined the geometric center by tracing the femoral head and compared the location to the functional center determined from circumduction motions [12]. The methods agreed to within 0.5–1.3 mm, but the study did not evaluate other motion patterns. Multiplane motions have been shown to produce more accurate estimates of the true rotation center in mechanical linkages, and that circumduction that included 30° of flexion and adduction are the most accurate [16, 25].

The errors in estimating the hip center location have consequences in both surgical navigation and functional analyses of the hip. In surgical navigation systems, the hip center is often estimated using a functional analysis. In hip surgery, an error in the anterior direction of 4 mm would lead to an error in anteversion of 5° for a typical offset of 44 mm. The error in the medial–lateral direction would directly generate an error in lateral offset; however, the surgeon can easily compensate intraoperatively when adjusting the femoral component neck length for soft tissue tensioning. In navigated knee surgery, the mean 2 mm error in this axis would lead to an error of 0.3° in limb alignment for a 400 mm femur. The target limb alignment in total knee arthroplasty is usually within 3° of neutral to minimize the risk of component failure [26] so this error is unlikely to be clinically significant. The differences in hip center estimates are more likely to have an influence in functional investigations of the hip, such as analyses of muscle function and joint loads. These differences cause errors in the muscle moment arms of the functional models which have a strong influence on estimated muscle forces and consequently joint contact forces. The regression model produced large errors compared to the geometric center, especially in the anterior direction. This error decreases the moment arm of hip flexors and would therefore lead to an overestimate of the forces in those muscles in order to create sufficient flexion moment.

The practical significance of errors in estimating the hip center location thus depends on the application. This study has shown that circumduction and star motions produce results with similar accuracy compared to the geometric

center, but circumduction results had higher precision, i.e., smaller test–retest differences. Since previous studies with mechanical linkages have shown that achieving a rotation angle of 30° improves the accuracy, we recommend using circumduction with at least 30° of flexion and abduction when using a functional estimation of the hip center.

Disclosures Each author certifies that he or she has no commercial associations (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article.

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