Functional and Anatomic Orientation of the Femoral Head

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Abstract

Background Femoral neck geometry directly affects load transmission through the hip. Orientations may be described anatomically or using functional definitions that consider load transmission.

Questions/purposes This study introduces and applies a new method for characterizing functional femoral orientation based on the distribution of subchondral bone density in the femoral head and compares it with orientation measures generated via established anatomic landmark-based methods. Both orientation methods then are used to characterize side-to-side symmetry of orientation and differences between men and women within the population.

Patients and Methods A retrospective review of CT imaging data from 28 patients was performed. Anatomic orientation was determined using established two-dimensional and three-dimensional landmarking methods. Subchondral bone density maps were generated and used to

define a density-weighted surface normal vector. Orientation angles generated by the three methods were compared, with side-to-side symmetry and differences between genders also investigated.

Results The three methods measured substantially different angles for anteversion and neck-shaft angle. Weak correlations were found between anatomic and functional orientation measures for neck-shaft angle only.

Conclusions Neck-shaft angles calculated using the functional orientation method corresponded well with previous in vivo loading data. An absence of strong correlation between functional and anatomic measures reinforces the concept that bone geometry is not solely responsible for determining loading of the femoral head.

Level of Evidence Level II, Diagnostic Studies—Investigating a Diagnostic Test. See the Guidelines for Authors for a complete description of levels of evidence.

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Introduction

The orientation of the femoral head is important for understanding joint mechanics. It is described in terms of neck-shaft angle (NSA) and femoral anteversion. Femoral NSA is the angle of the femoral head in the coronal plane with reference to the shaft of the femur. The femoral neck anteversion angle refers to the angle of the head in the axial plane with reference to the posterior condylar axis (PCA). Femoral neck anteversion affects in- or out-toeing during gait, and after THA, it affects dislocation and ROM. These angles also determine how force is transmitted through the femoral soft tissue and influence hip mechanics. As such, femoral neck orientation has been shown to have implications in the pathogenesis of osteoarthritis [16].

To date, investigations of native femoral neck geometry have shown large variations between studies, with average anteversion values ranging from 8° to 19° [2, 11, 13, 17] and average NSAs ranging from 125° to 133° [8, 13, 17]. The intermethod variations, however, are larger than the differences seen within the various populations. A lack of consistency in the methods (including the definition of landmarks) used to determine NSA and anteversion in the various studies may explain this finding.

Orientations may be defined by anatomic measurements, but other functional definitions also have been used to describe bony orientation through the consideration of load transmission vectors [1]. A functional definition of orientation would reflect the active contact surfaces of the femoral head that represent joint forces. However, functional orientation is difficult to measure as the orientation of force transmission through the hip changes with time and with activity and is not immediately apparent based on geometric features. Furthermore, in vivo force transmission only can be measured using instrumented prostheses, which are not appropriate for implantation in a large subject body.

As bone adapts to the forces it experiences, the distribution of subchondral bone densities around the femoral head may be reflective of the sum of the different loads transmitted through the head during the life of the hip. Using this concept, mapping the subchondral bone density distribution of the femoral head could further elucidate the direction, relative magnitude, and duration of forces transmitted through the hip to represent functional femoral orientation.

The purpose of this study is to introduce and apply a new method for characterizing femoral anteversion and NSA that represents a more functional orientation based on bone density distribution. Specifically, this work aims to compare the novel functional orientation with orientation measures generated via established anatomic landmark-based methods, and both orientation methods then are used to characterize side-to-side symmetry of orientation and differences between men and women within the population. We hypothesize the proposed functional measurements of orientation will be correlated to the existing methods of anatomic measurement.

Patients and Methods

A retrospective review was performed of CT imaging data acquired for evaluation of nonorthopaedic disorders (GE LightSpeed VCT [GE Corp, Fairfield, CT, USA] helical scans with 2.5-mm slices spaced 1.25 mm apart) for 28 individuals (13 males, 15 females; mean age, 69 years) at our institution. The scans were selected based on a list of all patients with CT images of the pelvis and full lower

extremity acquired at our institution during a 3-month period. These images were screened sequentially to ensure the absence of osteoarthritis of the hips, knees, and ankles, trauma, or tumors in either the pelvis or lower extremity and the first 28 scans meeting our inclusion criteria were used. The CT scans were analyzed with custom code written on the AmiraDev 4.1 platform (Visage Imaging, Carlsbad, CA, USA).

Anatomic orientation was determined by manually placing sets of landmarks on reconstructed CT volume data. Two methods, one two-dimensional (2-D) and the other three-dimensional (3-D), previously developed and applied by Lee et al. [11], were used to characterize the anatomic native femoral neck orientation and identify all bony landmarks. The detailed criteria used to identify each landmark described by Lee et al. [11], including CT slice selection and spatial localization in a given slice, were followed in our procedure to place all landmarks and construct the axes. Minor modifications were made to their protocol in the use of a different software platform for image analysis (AmiraDEV) and the use of three simultaneously displayed orthogonal slices to further improve localization of the bony landmarks, which then were verified on a 3-D surface model. Landmarks were used to create four geometric axes (Fig. 1). (1) The landmarks of the femoral head center (FHC) and the femoral neck center (2DFNC) were joined to create the 2-D femoral neck axis (2DFNA). (2) The landmarks of the 3-D femoral neck center (3DFNC) and the 3-D femoral head center (3DFHC) were joined to create the 3-D femoral neck axis (3DFNA). (3) The landmarks of the lateral and medial apices of the posterior condyles (LAPC and MAPC) were joined to create the PCA. Finally, (4) the landmarks of the proximal-most neck confluence (PNC) and the intracondylar notch center (ICNC) were joined to create the femoral anatomic axis (FAA).

The anatomic 2-D method that most closely approximates current clinical practice uses landmarking on 2-D axial CT cuts perpendicular to the mechanical axis of the femur, defining the 2DFNC as the center of the most proximal axial neck cut. The anatomic 3-D method uses the ability of AmiraDev to display three orthogonal views simultaneously on which the geometric center of the neck can be chosen and verified (previous work has used only axial and coronal views for 3-D landmarking [11]). Before landmarking of the 3DFNC, the femur was rotated in the coronal plane using an estimation of the NSA. This rotation oriented the axial CT slices approximately parallel to the neck [11], simulating the cut along the angle of neck inclination used by previous authors to more accurately define the 3DFNC [10, 18].

To determine the functional orientation of the femoral head, the reconstructed CT data were semiautomatically

Fig. 1A–C The landmarks used to determine femoral orientations are shown. (A) The landmarks are connected to form axes for calculation of femoral anteversion and NSAs. The interface used to determine (B) 2DFNC and (C) 3DFNC contains three orthogonal views of the CT data.

segmented with a 3-D atlas-based approach to define only the femoral head. An atlas data set, consisting of CT scan data and a previously obtained segmentation of the femoral head, was aligned to each subject scan with an affine registration followed by a morphing with level set motion that outlined the outside of the cortical shell on each axial, sagittal, and coronal slice. This semiautomatic approach allowed for high-quality 3-D segmentations to be quickly generated for each patient. The 3-D femoral head segmentation was then shrunk 2.5 mm into the cortical bone and the CT scans were resampled at a resolution of 5 mm. The surface bone density maps were calculated based on the intensity of each surface voxel (5-mm isotropic voxel size). A 5-mm thickness was used based on reported thickness of subchondral bone [3, 4, 9]. The surfaces were trimmed manually along the physal scar to isolate the articular surface of the femoral head. The functional femoral neck axis (FFNA) was defined as the density-weighted average of the femoral head surface normal vectors. The FFNA was determined using the density map, generated by mapping the gray values from the CT data onto the shrunk femoral head surface, and a set of surface normals

(generated by AmiraDEV) for the femoral head surface. At each point on the surface, the surface normal was multiplied by the density. These 3-D vectors then were averaged over the entire surface of the head. This vector represents the orientation of the femoral head bone density, thus describing a functional axis (Fig. 2).

For each of the three measurement methods described (2DFNA, 3DFNA, and FFNA), femoral neck orientation was characterized by the anteversion angle (measured relative to the PCA in the axial plane) and NSA (measured relative to the FAA in the coronal plane) (Fig. 2). These angles were measured in-plane using projections of the 3-D vectors generated using the three methods. Analyses were conducted on the left and right femora from each CT image. Pearson's correlation analyses were used to determine whether any relationships existed between the different measurement methods and within each measurement method to examine whether orientation was maintained in comparing the left and right femora. Significant differences ($p < 0.05$) were calculated using paired *t* tests where applicable. Analyses were conducted using SPSS[®] for Windows[®] (SPSS Inc, Chicago, IL, USA).

Fig. 2A–B The femoral head density map used to create the FFNA is shown. **(A)** The image is superimposed on an axial CT slice of the femoral condyles (used to calculate anteversion). **(B)** The femoral head density map is superimposed on a 3-D surface reconstruction of

the femur, shown in the coronal plane (used to calculate NSA). Density maps showed a consistent region of high density (red) on the **(A)** posterior and **(B)** superior portions of the head.

Table 1. Anteversion and neck-shaft angles

Method	Anteversion angle (°)			Neck-shaft angle (°)		
	Left	Right	Average	Left	Right	Average
2-D anatomic	9.0 (5.9)	8.6 (6.5)	8.8 [†]	107.6 (6.1)	108.2 (6.8)	107.9 [†]
3-D anatomic	13.2 (8.6)	12.5 (9.0)	12.8 [†]	140.7 (6.2)	139.3 (6.5)	140.0 [†]
Functional	−7.2 (10.1)	−12.8 (9.9)	−10.0 [†]	148.1 (11.3)	150.8 (8.5)	149.5 [†]

Values are expressed as average, with SD in parentheses; [†]indicates significant difference between methods ($p < 0.001$); 2-D = two-dimensional; 3-D = three-dimensional.

Results

Anteversion and NSAs were calculated bilaterally for 28 patients using the 2-D anatomic, 3-D anatomic, and functional orientation methods (Table 1). Differences in calculated angles were found between the three methods for anteversion ($p < 0.001$) and NSA ($p < 0.001$) measurements, with the functional orientation method exhibiting retroversion (negative anteversion) and a more vertically directed orientation vector than both anatomic measures (Fig. 3). Additionally, subchondral bone density distribution maps showed a consistent high-density localization on the superior and posterior portions of the femoral head. Based on the Pearson correlation analysis, strong correlations were found between the 2-D and 3-D anatomic orientation methods for anteversion and NSAs ($R = 0.77$, 0.87 ; $p < 0.0001$). In contrast, only a very weak correlation was found between the anatomic NSAs and functional NSA (2-D, $R = 0.28$, $p = 0.039$; 3-D, $R = 0.28$, $p = 0.036$), and no significant correlations were found for anteversion.

Moderate correlations were found between right and left sides using the 2-D and 3-D anatomic orientation methods

for anteversion and NSAs (2-D, $R = 0.70$, 0.56 ; $p < 0.05$; 3-D, $R = 0.63$, 0.41 ; $p < 0.05$), with no differences observed between left and right sides for any of the three methods ($p < 0.05$). Moderate correlation was found similarly between right and left sides for NSA using the functional orientation method ($R = 0.51$, $p < 0.005$); however, no side-to-side relationship was found for anteversion using the functional orientation method.

Analysis of the data by gender revealed differences in both anatomic anteversion measurements between males and females, with females on average having anteversion angles 4.3° and 6.0° greater than males ($p = 0.008$, $p = 0.009$) for the 2-D and 3-D methods, respectively (Table 2). No differences were found between males and females in NSA or in either of the functional measurements.

Discussion

The purpose of this study was to describe a novel method of calculating functional orientation of the human femoral

Fig. 3A–B A 3-D visualization of the mean (A) anteversion angles and (B) NSAs calculated for the three measurement methods (2DFNA, 3DFNA, and FFNA) are shown. Anteversion angles were measured relative to the PCA, and NSAs were measured relative to the FAA.

Table 2. Anteversion and neck-shaft angles measured for males and females

Method	Anteversion angle (°)		Neck-shaft angle (°)	
	Male	Female	Male	Female
2-D anatomic	6.5 (5.2) [†]	10.8 (6.4) [†]	109.2 (7.0)	106.7 (5.7)
3-D anatomic	9.6 (6.9) [†]	15.6 (9.3) [†]	141.6 (6.8)	138.7 (5.6)
Functional	−10.7 (10.6)	−9.4 (10.2)	149.4 (8.6)	149.5 (11.2)

Values are expressed as average, with SD in parentheses; [†]indicates significant difference between males and females ($p < 0.01$); 2-D = two-dimensional; 3-D = three-dimensional.

head using the distribution of subchondral bone density and to compare the angles measured using this method with established anatomic measurement methods. The functional orientation method has been shown to calculate angles substantially different from those calculated by both anatomic orientation methods investigated. This study also investigated side-to-side symmetry and male/female characteristics of anteversion and NSAs calculated using anatomic and functional orientation methods. Symmetry was found between corresponding left and right anatomic orientations only. Females were found to have significantly higher anatomic anteversion, but there was no significant difference functionally.

The subchondral bone density-based functional orientation method described here is limited in that, as a

CT-based measure, patients with metal hardware or other implanted devices that create image artifacts may not be possible to analyze. Although this may limit the usefulness of this measure for situations involving traumatic injury postinstrumentation, assessment of native bone and progression of bone disorders can be successfully performed. The variability in the orientations calculated indicates the sensitivity of this measurement technique to small changes in surface geometry. Similar variability has been seen in previous geometric measurement techniques [7, 11, 15, 17]. Variability in the functional orientation measure is reduced through automatic segmentation of the femoral head and cropping of the femoral head density maps using the physal scar.

The average anteversion angle calculated for the 2-D method (8.8°) was similar to the 8.6° calculated by Lee et al. [11] using the similar modified ISS method and was within the range of average values seen in other studies of femoral anteversion [2, 13, 17]. However, the average anteversion angle calculated for the 3-D method (12.8°) was less than the 18.5° calculated by Kim et al. [10] using the 3DFNC method. Although this may be an artifact of the differences previously shown between measurement methods, different anteversion measurements documented for different races [7] and higher average anteversion seen for females in our study may be responsible for the increased anteversion seen in the all-female Korean patient cohort [10]. However surprisingly, functional anteversion

was not different between males and females, suggesting similar loading directions despite differing geometries.

The modified ISS and 3-D methods were not used previously to measure NSA, but the NSAs calculated using the 3-D method are within the range of previous measures using other methods [17]. The NSAs calculated using the modified ISS method, however, are substantially less than any previously reported. Although the modified ISS method yielded different results, this discrepancy can be explained by the more superior placement of the 2DFNC compared with the 3DFNC landmarks and those used in previous studies (Fig. 2).

Although average anteversion and NSA values reported in the literature are 8° to 19° and 125° to 133° , respectively, the range of measurements varies widely from -15° to 40° in anteversion and 105° to 145° in NSA. This large range in the normal population also has indicated specific differences in these angles between races [7]. Other studies have shown meaningful differences occur between different measurement methods and observers in quantifying femoral anteversion and NSA [11, 15]. Our study furthers the existing literature in that it incorporates bone density into determining orientation and investigates symmetry between the left and right femurs. An advantage of using the functional orientation is the ability to determine orientation without the need to define the center of the femoral neck, which is responsible for much of the inter-observer variability reported in other studies.

Anatomic orientations did not change between left and right sides, with average differences between sides ranging from 4° to 6° . Although this difference seems appreciably large, the substantial variation seen within the population causes the side-to-side differences to be small in comparison. However, the absence of a more robust correlation between sides precludes one side being able to accurately predict the anatomic measures of the other side. This type of prediction would be useful in preplanning for many surgical interventions.

The absence of strong correlations between anatomic and functional measurements indicates bone geometry is not the only factor that affects the nature of weightbearing through the femur. Differences between the 3-D and functional measurements indicate the direction of average applied loading from the pelvis to the femur is not through the geometric center of the femoral neck. The direction of loading appears to be directed more vertically, as evidenced by the larger NSAs calculated for the functional orientation method. Additionally, density maps indicated there is generally a high-density region located on the posterior side of the head (Fig. 2), resulting in a measure of negative functional version (retroversion) that is opposite the anteversion seen for the anatomic orientation. This localization of bone density on the posterior portion also

contrasts with the previously described anteverted in vivo loading distributions, indicating the relationship between contact forces and subchondral bone density along the anterior-posterior axis may require more than just studies of instantaneous loading.

The orientation of in vivo loading of the femoral head was investigated by Bergmann et al. [1] using an instrumented prosthesis during various tasks of daily living. They found average loading orientations ranging from 28° to 35° relative to the PCA (analogous to anteversion) and 7° to 16° relative to the midline of the femoral shaft (analogous to NSAs of 164° – 173°) [1]. The average values for NSA calculated by the two studies are consistent and indicate an orientation steeper than the native NSA. The negative functional anteversion angles calculated in our study differ from the values reported by Bergmann et al. [1], which are highly anteverted. Although these findings seem to be contradictory, the large variability in in vivo loading observed within and between patients indicates the need for paired testing to be done to compare loading orientation with bone density.

Orientation of the trabecular structures underlying the subchondral bone has been well documented since the introduction of this concept by Gray et al. [5]. This organization of trabeculae includes a primary compressive group that runs from the upper portion of the femoral head to the medial side of the shaft. The areas of high subchondral bone density observed on the superior portion of the femoral head in our study correspond well qualitatively with the region of compressive trabecular orientation described by Gray et al. [5]. This suggests a relationship between the loading experienced by the cortical bone and the underlying trabeculae, indicating primary weightbearing through this region of high subchondral bone density in the superior femoral head.

This work represents a novel approach for determining and describing the distribution of subchondral bone density in the femoral head. A similar approach used to map bone density distribution in the proximal tibia was described by Johnston et al. [9], which allowed them to successfully generate bone density distribution maps at prescribed depths of cortical bone. Previous investigation of femoral head bone density distribution has been limited to using finite element modeling of forces or 2-D quantitative CT-based approaches [14].

The limitation of the CT-based approaches to date has been their inability to effectively represent the distribution over the whole surface of the femoral head in 3-D. Studying change in subchondral density and distribution may be of particular importance for tracking the development of osteoarthritis. Osteoarthritic joints have been shown to have thicker, less mineralized subchondral bone layers [6]. In our study, subchondral bone density and

distribution were examined using reconstructed CT data to create surfaces that outline the entire femoral head, onto which the bone density values can be mapped. This method was developed previously and used by us to illustrate the subchondral bone density distribution of the acetabulum [12]. The orientations of highest bone density in our study align with those found for the acetabulum in that the functional orientation vector is directed more superior and posterior than the native geometry.

The distribution of bone density observed in our study elucidates the limited role of bone geometry and possible importance of the soft tissue structures in load transmission in the lower extremity. This new functional method of accessing orientation has been shown to measure angles different from those measured by the anatomic methods and shows functional loading of the femoral head cannot be correlated directly with anatomic parameters. Clinical adoption of image analysis techniques is feasible with the widespread use of digital imaging and robust automated computational tools. Future studies will incorporate this functional measurement tool into investigations of hip disorders and combine knowledge of acetabular orientation with femoral head orientation to further improve our understanding of the hip and its function in healthy and disease states.

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