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The Three-Dimensional Shape of the Dysplastic Femur

Implications for THR

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This study evaluates the three-dimensional anatomy of the femur with congential dysplasia of the hip (CDH) in comparison with healthy controls. Computed tomographic scans were obtained from 207 women (154 with dysplasia; 53 healthy controls) with an average age of 51.6 years (range, 18–82 years). Most of the dysplastic joints were classified as Crowe I (43%), or Crowe II or III (48%), with 9% Crowe IV. Individualized three-dimensional computer models of the femur were generated by reconstruction of the CT scans. Dimensional and morphometric parameters were derived by computer analysis of each of the femoral reconstructions. The dysplastic femurs had shorter necks and smaller, straighter canals than the controls. The shape of the canal became more abnormal with increasing subluxation. Detailed analysis showed that the primary deformity of the dysplastic femur is rotational, with an increase in anteversion of 5° to 16°, depending on the degree of subluxation of the hip. The rotational deformity of the dysplastic femur arises within the diaphysis between the lesser trochanter and the isthmus and is not attributable to a torsional deformity of the metaphysis. This study shows that there is a significant difference in the geometry of the normal femurs and those with CDH, even in mild cases. In CDH cases, we recommend the use of modular or specially designed components to accommodate the shape of the dysplastic canal.

Congenital dysplasia of the hip is the most common underlying condition leading to secondary osteoarthritis (OA) of the hip.[2,3,17,28] Although pelvic and femoral osteotomies may be done to

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prevent degenerative changes and restore coverage of the femoral head, many patients ultimately progress to having total hip arthroplasty (THA). Although arthroplasty often is the only definitive way of restoring the normal biomechanics of the dysplastic joint, these procedures often are challenging, primarily because of the associated bony deformities. Typically, the dysplastic joint consists of a subluxed or even dislocated femur with a straight, narrow canal and a short excessively anteverted neck, and a shallow, vertically-inclined acetabulum.[6–8,21,30] The increased surgical demands of the dysplastic joint often result in inferior results after total hip replacement (THR) with an increased incidence of loosening and dislocation at long-term followup.[5,9,11,15,19,22] These procedures also are associated with an increased prevalence of intraoperative complications, most notably cortical fracture, because of the difficulties of inserting conventional prostheses into canals of distorted shape and version.[11,26]

Clinical experience suggests that the anatomic abnormalities inherent in the dysplastic femur increase with the degree of subluxation of the hip.[7,16,29] Consequently, the technical difficulty in doing joint replacement, and the appropriate design of the femoral prostheses are related to the severity of the disease through its impact on femoral morphology. Nonetheless, there have been few detailed, scientific studies of the morphometry of the dysplastic femur. Many previous investigators have reported the bony dimensions derived from plain radiographs or CT scans of small groups of patients with CDH of various degrees of severity, without age-matched or gender-matched controls with normal anatomy.[8,23,31] However, because the size and shape of the human femur varies with the gender, age, stature, and ethnic background of each individual,[18] it is not possible to isolate the effect of dysplasia on the shape of the femur.

Because CDH is relatively uncommon in the American and European population, and because the majority of adults with dysplasia have been treated with prior surgery, it virtually is impossible to isolate the effects of secondary variables in studying the pathologic morphologic characteristics of these populations. Conversely, in the Japanese population, excessive femoral anteversion and congenital dysplasia of the hip are relatively common. Moreover, more than 90% of all osteoarthritis of the hip is secondary to hip dysplasia, with many of these patients ultimately presenting for THA.[16] Because many of these patients present for orthopaedic evaluation without any prior operative treatment, Japan is an ideal place to study the natural history of hip dysplasia and the morphologic characteristics of the dysplastic hip. In view of these benefits, the femoral morphologic characteristics of healthy patients and patients with dysplasia were studied at three major orthopaedic centers in Japan located in Osaka, Tokyo, and Chiba. The aim of this study was to evaluate the hypothesis that: in the adult patient with dysplasia, the three-dimensional anatomy of the femur differs fundamentally from the normal femur internally and externally, and the severity of the abnormality of the dysplastic femur is related to the degree of subluxation of the hip.

MATERIALS AND METHODS

One hundred fifty-four women with congenital dysplasia of the hip were selected from three academic institutions for analysis in this study. All patients were at least 18 years (average age, 52.1 years; range, 18–82 years), and presented with varying degrees of hip subluxation. The patient population was divided into three groups according to the severity of hip dysplasia, as indicated by the classification of Crowe et al.[7] Group I (Crowe I, < 50% subluxation) consisted of 68 hips (44%), Group II (Crowe II or III, 50%–100% subluxation) consisted of 71 hips (46%), and Group III (Crowe IV, > 100% subluxation), consisted of 15 hips (10%). None of these patients had an osteotomy for treatment or correction of their hip disease. Patients with radiographic evidence of joint degeneration or total ischemic necrosis of the femoral head were excluded.[4]

Patients in Group I had an average age of 47.1 ± 16.7 years (range, 18–82 years), compared with 54.9 ± 12.7 years for Group II (range, 18–82 years) and 61.2 ± 8.5 years for Group III (range, 47–79 years). An additional group of 53 age-matched women (average age, 50.3 ± 17.3 years; range, 19–78 years) was chosen to serve as a healthy anatomic control. These patients had radiologic investigation of nontraumatic osteonecrosis (ON) of the femoral head or rheumatoid arthritis (RA) and had at least one hip that was radiologically normal without collapse of the femoral head or erosive changes.

Transverse images were obtained of each femur using a helical CT scanner (CT HiSpeed Advantage RP, GE, Milwaukee, WI). During scanning, the hip and knee of each patient was extended fully with the lower limbs secured to the table with a below-knee splint that fixed the rotational position of the extremity. Positioning was checked by AP and lateral scout views. Computed tomography images of all patients were obtained using similar scanning protocols with some variations according to the medical center. The area of the femur from the top of the femoral head to below the lesser trochanter was scanned with 3-mm thick transverse slices spaced either 3 or 5 mm apart. In the femoral midshaft, slices of 3-mm in thickness were obtained with 10-mm spacing, and several serial 3-mm slices were taken through the femoral condyles.

Dimensionally accurate, patient-specific computer reconstructions were generated from the CT files of each femur to allow calculation of the dimensional variables describing the size and morphologic characteristics of each femur (Fig 1). In the first stage of the bone reconstruction process, spatial coordinates defining the inner (endosteal) and outer (periosteal) contours of the femur were extracted using automatic and semiautomatic software tools, as indicated. This process allowed accurate representation of the periosteal and endosteal borders of the femur. In the second stage of the reconstruction process, the coordinate data were segmented into subsets describing the surfaces of seven anatomic objects that make up each femur: the femoral head, the neck, the greater and lesser trochanters, the femoral shaft, and femoral condyles (Fig 2). Numerical routines were developed to describe the relative displacement and rotational orientation of each of these anatomic objects with respect to those adjoining it.

Three-dimensional, surface-splined models of the femoral shaft region were constructed to

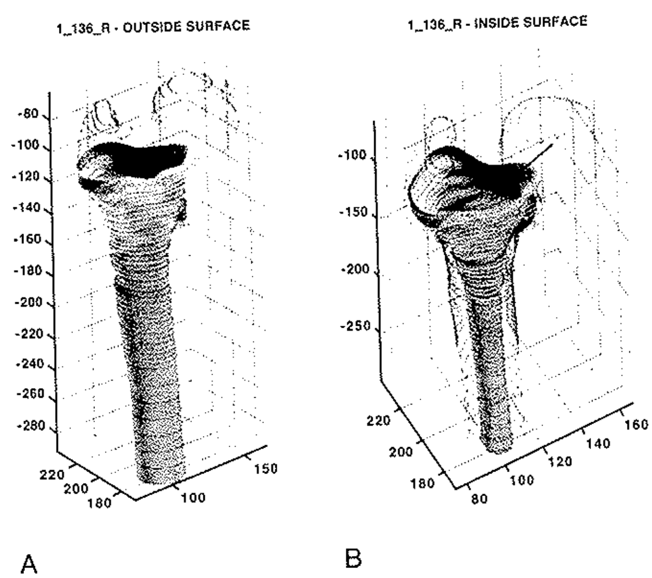

Fig 1A–B. Typical computer reconstructions show the femur in which the (A) inner, and (B) outer surfaces of the canal have been rendered after stacking contours extracted from CT scans.

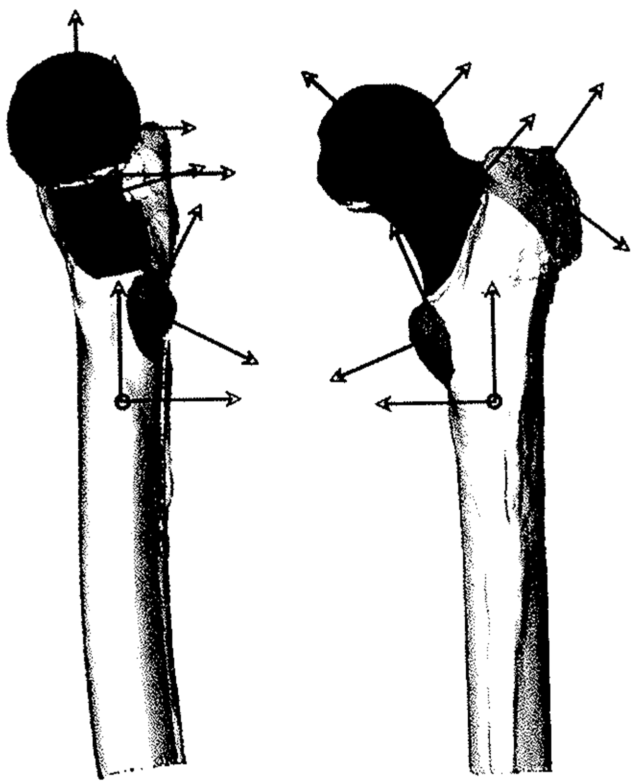

Fig 2. Each computer model of the proximal femur was segmented into components corresponding to the femoral head, the neck, the shaft, and the greater and lesser trochanters. Each of these three-dimensional objects was attached to an origin (indicated by the open circles), and a set of axes (indicated by the arrows).

enable interpolation between the levels of the original CT scans. Where necessary, datum points and axes describing the position and orientation of each region also were computed. Most morphologic parameters were calculated in a coordinate system (the cone-neck coordinate system) containing the longitudinal axis of the femur (as defined by the axis of a cone fitting the medullary canal), and the axis of the femoral neck. To orient each three-dimensional femoral model in this coordinate system, the model was translated and rotated until the axis of the femoral implant coincided with the external world coordinate system. Next, the model was rotated until the neck axis became parallel with the horizontal plane. Some morphologic parameters, most importantly, the anteversion of the proximal femur, were measured in a coordinate system (the cone-table coordinate system), defined by the axis of the femoral neck and a tangent to the posterior borders of the medial and lateral condyles.

The following parameters were generated for each femur. The axis of the medullary canal was defined as the longitudinal axis of the cone of best fit to the midshaft. The shape and orientation of the best fit cone was calculated by a numerical optimization routine that varied the length, diameter, and taper angle of a virtual intramedullary rod until the aggregate volume of gaps between the outer surface of the cone and the endosteal surface of the femur was minimized. The point within the diaphysis where the cone of best fit to the canal penetrated the endosteal surface of the anterior cortex was chosen to define the upper border of the anterior bow of the canal. The depth of the anterior bow then was defined by the distance along the medullary axis from this upper border to the center of the lesser trochanter.

The femoral neck and femoral head were modeled separately to enable examination of their anatomic relationship. A computer-based procedure was developed to represent the head and neck as solid bodies with orientations and positions in space defined by centroids and axes. This formal procedure was done because of the inaccuracy of simpler methods of calculating femoral anteversion that have been reported by several investigators.[20,29] The center of the femoral neck was defined as the centroid of a transverse slice taken through the neck at its narrowest point, whereas the femoral neck axis was calculated as the line of best fit to the parallel sections of the cortices of the neck, as seen in six slices taken radially at 30° intervals along the predicted neck axis. The length of the femoral neck was defined as the distance between two points on the neck axis, one located closest to the center of the femoral head and the other closest to the medullary axis.

The center and diameter of the femoral head were defined by averaging three circles of best fit to sections through the femoral head data oriented at 70°, 90°, and 120° relative to the femoral neck axis. In contrast, calculations based on a sphere of best fit are complicated by the presence of a portion of the femoral neck. The offset of the head center from the medullary axis then was resolved into its medial and anterior components within the plane of the femoral neck. The height of the head center also was calculated as the distance from the center of the lesser trochanter to the center of the femoral head parallel to the medullary axis.

As the femoral neck is placed in an anterior location on the shaft of the femur, the anterior femoral neck offset was defined as the AP component of the shortest line connecting the femoral neck axis and the medullary canal axis. The neck-shaft angle was defined as the angle be0tween the medullary axis and the neck axis, projected onto the plane of the neck. Neck anteversion was defined as the angle between the femoral neck axis and a tangent to the posterior femoral condyles in a plane perpendicular to the medullary axis.

The isthmus of the medullary canal was defined by calculating the diameter of the largest circle, centered on the canal axis, that could fit within the endosteal boundary. The width of the canal was measured in planes parallel to, and perpendicular to, the femoral neck. These measurements were taken at the following four levels, normalized to the height of the femoral head above the center of the lesser trochanter (HFH): 0.35 HFH (approximately 20 mm) above and below the center of the lesser trochanter, at the level of the lesser trochanter, and at the level of the canal isthmus (Fig 3). The canal flare index was calculated as the ratio between the mediolateral widths of the medullary canal measured at two levels: 0.35 HFH proximal to the lesser trochanter, and at the canal isthmus. Additional flare indices also were calculated from the ratio of canal widths at other levels within the canal.

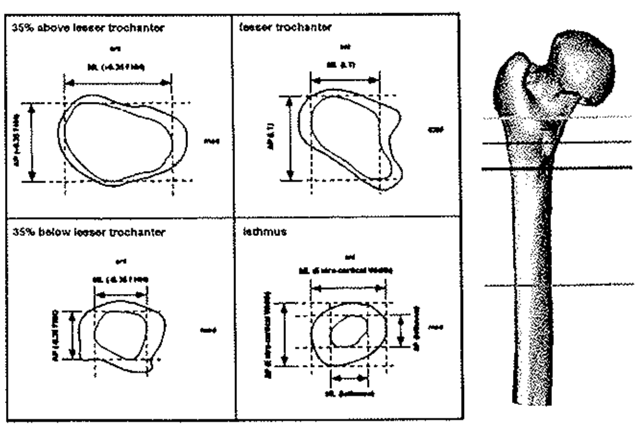

Fig 3. This figure shows the parameters that were chosen to represent the size of the medullary canal. The width of the canal was measured at four levels from the base of the femoral head to the canal isthmus, in directions parallel and perpendicular to the femoral neck axis.

The extracortical (external) width of the femur also was measured at the level of the isthmus, in the mediolateral direction. The cortical index was calculated as: 100(1- Di/Do), where, Di is the endosteal width of the femur at the level of the isthmus, and Do is the periosteal width of the femur at the level of the isthmus.

The medial inclination of the femoral neck was defined as the angle between the medullary axis and a line connecting two points on the endosteal border of the medial cortex, one at the level of the lesser trochanter, and the other 20 mm more proximal. To describe the twist or rotation of the femoral canal, the ellipse of best fit to the endosteal surface was calculated. We then measured the angle between the major axis of the ellipse and a tangent to the posterior aspect of the femoral condyles was measured. For sections through the femoral metaphysis, where the endosteal profile was not closely matched by an ellipse, the canal shape was represented by two circles: one matching the curvature of the medial cortex, and the second corresponding to the largest circle that could be placed within the endosteal contour. A line connecting the centers of both circles defined the rotational orientation of the canal with respect to the tangent to the posterior femoral condyles.

The statistical significance of associations among each of the anatomic parameters and the severity of hip dysplasia (coded as Normal, Crowe I, Crowe III/III, and Crowe IV) was evaluated using ANOVA. Statistically significant associations also were explored using pairwise t tests with a Bonferroni correction for multiple comparisons. Based on post hoc analysis, the threshold value for statistically significant differences was set at $p = 0.005$ to reduce the risk of Type 1 error.

RESULTS

Data describing each of the parameters measured in this study are presented in Tables 1 and 2. Average values of each parameter for the dysplastic femurs and normal controls are shown in Table 1. The same data are stratified by Crowe index in Table 2.

Dysplastic Femur Versus Healthy Controls

There were significant differences in the size and shape of the femurs of the 154 patients with hip dysplasia when compared with the 53 healthy controls (Table 1). Externally, the dysplastic bones were slightly smaller (1%–7%) than the controls, the magnitude of the difference varying with the specific parameter. The largest differences were seen in the height of the head center above the lesser trochanter (7%, $p = 0.018$), the medial head offset (8%, $p = 0.0014$; Fig 4), the length of the femoral neck (5%, $p = 0.007$), and the extracortical diameter of the diaphysis (isthmus level) (5%, $p < 0.0001$).

A different pattern was present within the endosteal cavity. In general, the canals of the dysplastic femurs were smaller than the normal femurs in the lateral projection but were of similar size in the AP projection. The only exception to this generalization was in the most proximal level of the canal, close to the inferior edge of the femoral head (35% of the femoral head height above the lesser trochanter), where the dysplastic canals were 2 mm narrower in the mediolateral direction ($p = 0.005$). Farther distally, the difference in mediolateral canal width of the normal and dysplastic groups was less than 2% at each of the levels examined. In the

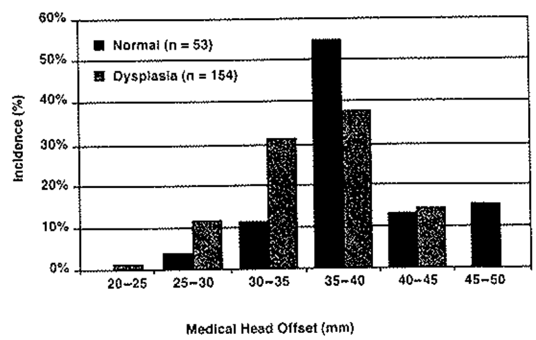

Fig 4. The graph shows the distribution of the medial head offset of the dysplastic femurs compared with healthy controls.

TABLE 1. Anatomic Parameters for Control and Dysplastic Femora

Parameters	Control	Dysplastic Cases	% change	p value
Femoral Head				
Height (mm)	47.9 ± 6.2	44.9 ± 8.5	7	0.018
Diameter (mm)	42.8 ± 2.5	44.2 ± 5.1	−3	0.054
Asphericity (%)	1.7 ± 1.1	3.2 ± 2.2	−48	0.000
Medial Head Offset (mm)	38.7 ± 4.7	35.9 ± 4.9	8	0.000
Anterior Head Offset (mn)	2.5 ± 2.9	1.1 ± 3.4	128	0.009
Anteroposterior Neck Offset (mm)	3.7 ± 2.3	3.0 ± 2.7	23	0.088
Neck length (mm)	47.7 ± 4.8	45.2 ± 5.9	5	0.007
Neck-shaft Angle (degrees)	124.3 ± 6.8	124.5 ± 10.1	0	0.897
Anteversion (degrees)	35.6 ± 13.7	42.3 ± 16.0	−16	0.007
Height of Greater Trochanter	53.2 ± 4.9	50.8 ± 5.8	5	0.007
Extracortical diameter of the diaphysis (ML, mm)	24.8 ± 1.8	23.7 ± 1.7	5	0.000
Medio-lateral canal width (mm)				
At 35% of head center height above Lesser Trochanter	41.7 ± 3.6	39.7 ± 4.9	5	0.005
At Lesser Trochanter	27.5 ± 3.6	27.2 ± 4.5	1	0.627
At 35% of head center height below Lesser Trochanter	20.2 ± 3.8	20.0 ± 3.9	1	0.791
At isthmus	12.7 ± 2.4	12.4 ± 1.9	2	0.427
Antero-posterior canal width (mm)				
At 35% of head center height above Lesser Trochanter	28.6 ± 2.6	28.0 ± 2.8	2	0.185
At isthmus	13.9 ± 3.2	12.9 ± 2.9	8	0.037
Canal Diameter at the Isthmus (mm)	10.8 ± 2.3	10.1 ± 1.6	7	0.015
Cortical Index	0.49 ± 0.09	0.48 ± 0.07	3	0.310
Medial Inclination (degrees)	152.3 ± 5.8	153.2 ± 7.4	−1	0.421
Isthmus Position (mm)	109.3 ± 15.8	106.4 ± 17.7	3	0.289
Cone Angle (degrees)	2.2 ± 1.5	1.6 ± 1.1	38	0.002
Cortical Thickness (mm)	6.1 ± 1.2	5.6 ± 0.9	7	0.009
Canal Flare Index	3.39 ± 0.61	3.26 ± 0.55	4	0.17

AP direction, the difference was 0.6 mm at the most proximal level (p = 0.185), increasing to 1.0 mm at the level of the canal isthmus (13.9 mm versus 12.9 mm; p = 0.037). A consequence of these differences was that the dysplastic femurs had straighter canals than their normal counterparts, as indicated by a difference in the canal flare index (dysplastic femurs, 3.26 versus controls, 3.39; p = 0.17) and the cone angle within the midshaft region (dysplastic femurs, 1.62°; controls, 2.24°; p = 0.002).

The greatest impact of dysplasia on femoral morphologic characterisitics was observed in the neck of the femur. The dysplastic femurs had shorter necks (dysplastic femurs, 45.2 mm versus controls, 47.7 mm; p = 0.007), oriented in an average of 6.7° more anteversion than the controls (p = 0.007; Fig 5). On average, there was no significant difference in the neck-shaft angle of the two groups (dysplastic femurs, 124.5°; normal femurs, 124.3°; p = 0.897; Fig 6). Moreover, when oriented in the plane of the femoral neck, none of the femurs examined had a neck-shaft angle greater than 140°, despite the appearance of many femurs when oriented in the coronal plane. Nonetheless, there was much greater variation in neck inclination in the dysplastic group compared with the normal controls, with a significant prevalence of coxa vara and coxa valga.

TABLE 2. Anatomic Parameters for Control and Dysplastic Femora by Severity of Dysplasia

Parameters	Control	Crowe I	Crowe II/III	Crowe IV
Femoral Head				
Height (mm)	47.9 ± 6.2	47.0 ± 8.3	43.7 ± 8.6*	41.0 ± 6.8*
Diameter (mm)	42.8 ± 2.5	43.3 ± 2.7	46.0 ± 5.5*	40.1 ± 7.5
Asphericity (%)	1.7% ± 1.1%	2.0% ± 1.0%	4.2% ± 2.4%*	4.6% ± 2.4%*
Medial Head Offset (mm)	38.7 ± 4.7	36.5 ± 4.9	35.6 ± 5.1*	34.6 ± 3.4
Anterior Head Offset (mn)	2.5 ± 2.9	1.1 ± 3.0	0.5 ± 3.6*	4.2 ± 3.3
Anteroposterior Neck Offset (mm)	3.7 ± 2.3	3.0 ± 2.3	2.6 ± 2.9	5.1 ± 2.2
Neck length (mm)	47.7 ± 4.8	46.6 ± 5.0	44.8 ± 6.3*	40.8 ± 5.3*
Neck-shaft Angle (degrees)	124.3 ± 6.8	126.2 ± 8.3	123.9 ± 11.6	120.0 ± 8.1
Anteversion (degrees)	35.6 ± 13.7	45.4 ± 13.6*	38.3 ± 18.4	47.0 ± 8.3
Height of Greater Trochanter	53.2 ± 4.9	52.1 ± 4.6	49.3 ± 6.6*	52.2 ± 5.0
Extracortical diameter of the diaphysis (ML, mm)	24.8 ± 1.8	24.0 ± 1.6	23.6 ± 1.7*	22.3 ± 1.8*
Medio-lateral canal width (mm)				
At 35% of head center height above Lesser Trochanter	41.7 ± 3.6	40.0 ± 4.3	40.7 ± 4.3	33.0 ± 5.0*
At Lesser Trochanter	27.5 ± 3.6	26.8 ± 3.5	28.2 ± 4.9	24.6 ± 5.1
At 35% of head center height below Lesser Trochanter	20.2 ± 3.8	19.4 ± 3.3	21.0 ± 4.1	18.6 ± 4.3
At isthmus	12.7 ± 2.4	12.3 ± 1.7	12.5 ± 2.1	12.5 ± 2.4
Antero-posterior canal width (mm)				
At 35% of head center height above Lesser Trochanter	28.6 ± 2.6	28.1 ± 3.0	28.2 ± 2.5	26.5 ± 3.5
At isthmus	13.9 ± 3.2	12.1 ± 2.5*	13.7 ± 3.0	13.0 ± 3.1
Canal Diameter at the Isthmus (mm)	10.8 ± 2.3	9.8 ± 1.4*	10.4 ± 1.8	10.2 ± 1.9
Cortical Index	0.49 ± 0.09	0.49 ± 0.06	0.44 ± 0.08	0.47 ± 0.08
Medial Inclination (degrees)	152.3 ± 5.8	152.3 ± 7.0	154.4 ± 7.3	151.7 ± 10.5
Isthmus Position (mm)	109.3 ± 15.8	102.7 ± 14.7	108.2 ± 18.8	114.5 ± 21.2
Cone Angle (degrees)	2.2 ± 1.5	1.8 ± 1.2	1.5 ± 1.1*	1.1 ± 1.1*
Cortical Thickness (mm)	6.1 ± 1.2	5.9 ± 0.7	5.5 ± 1.0*	4.9 ± 0.7*
Canal Flare Index	3.4 ± 0.6	3.3 ± 0.5	3.3 ± 0.6	2.7 ± 0.5*

*Values Significantly Different from Control Femora ($p < 0.005$).

Effect of Severity of Dysplasia

The severity of hip dysplasia had a dramatic effect on the size and shape of the femur. In general, femurs from patients with more advanced subluxation were more hypoplastic, had greater deformity of the femoral head, and had straighter canals with thinner cortices. These changes were most profound in dislocated femurs (Crowe IV).

Surprisingly, even femurs with the mildest degree of subluxation (Crowe I) had noticeable alterations in morphologic characteristics, although most changes were isolated to the proximal femur. Crowe I femurs generally had less anterior and medial head offset, and a dramatic increase in anteversion in comparison with normal controls (Crowe I femurs, 45.4°; normal controls, 35.6°; $p = 0.0005$). The mediolateral width of the Crowe I canal was narrower above the level of the lesser trochanter, but did not differ from normal controls at all other levels. At the level of the isthmus, the canal was elliptical in cross section but seemed to be approximately the same width in the AP and lateral projections because of the twist of the femur secondary to increased anteversion (Fig 7). As a result, the narrowest diameter of the canal was greater than 2 mm smaller than the apparent width of the canal seen in the AP projection (Fig 8). On average, the

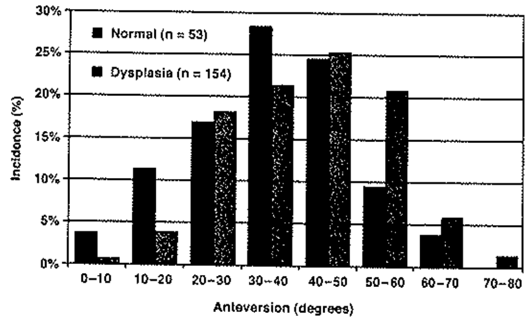

Fig 5. The graph shows the distribution of femoral anteversion of the dysplastic femurs compared with healthy controls.

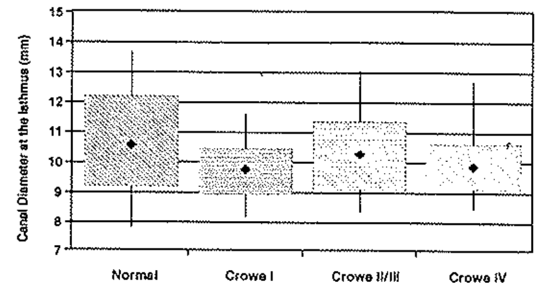

Fig 7. The graph shows the variation of the minimum diameter of the medullary canal for each of the groups of dysplastic femurs compared with the healthy controls.

minimum diameter of the canal was 1 mm smaller in the Crowe I femur (9.8 mm) than normal controls (10.8 mm; $p = 0.0028$). There was no significant difference between the average position of the anterior bow of the Crowe I femur compared with normal controls (Crowe I, 81.5 ± 14.7 mm; normal controls, 78.2 ± 18.4 mm; $p > 0.05$), however, femora with a high anterior bow (depth < 75 mm) were much more prevalent in the normal population than the Crowe I group (48% versus 26%) (Fig 9).

In many respects, the Crowe II/III femurs were smaller replicas of the normal femur in terms of extracortical dimensions. The medullary canal of the Crowe II/III femur was similar in size to the normal femur due to the thinner cortices of the dysplastic bones. The Crowe II/III femur was slightly smaller than the Crowe I femur, with an average decrease in many extracortical dimensions averaging 3% to 6%. The major

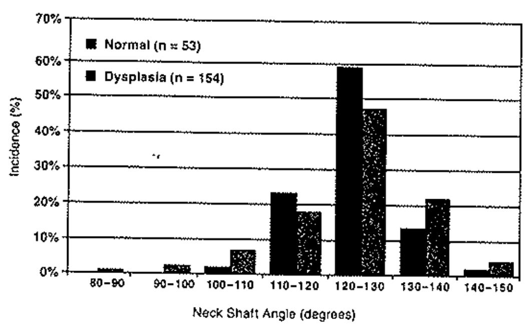

Fig 6. The graph shows the distribution of the neck shaft angle of the dysplastic femurs compared with healthy controls.

exception was the diameter of the femoral head which was slightly larger in the more subluxed femurs, although with even greater asphericity because of the marked incongruence of the hip. The medullary canals of Crowe II/III femurs were slightly wider than the Crowe I femurs in the mediolateral and AP directions, and also differed in terms of the depth of the anterior bow (Crowe II/III, 90.6 ± 18.5 mm; Crowe I, 81.5 ± 14.7 mm).

The Crowe IV femurs had the largest deviation in bony morphometry from the normal controls. Typically, these bones had a hypotrophic appearance. Compared with the normal femur, there was a 10% to 20% reduction in most parameters, including the neck length (83% of normal), the extracortical diameter (88%), and the cortical thickness within the diaphysis (76%). The femoral head of the Crowe IV femurs had less medial offset (87%) but more anterior offset when compared with the control group. There was a significant reduction (18% of $P < 0.001$) in the height of the head center above the lesser trochanter. This observation was consistent with the more horizontal inclination of the femoral neck of the Crowe IV femur, compared with normal controls (120.0 versus 124.3°). These femurs also were anteverted far in excess of the normal femur, with an average anteversion angle of 47° versus 35.6° for the control group ($p = 0.0032$).

There also was a dramatic difference in the shape and dimensions of the intramedullary canal

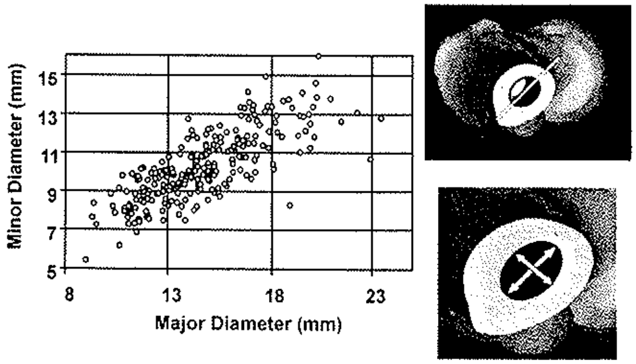

Fig 8. This scatterplot shows the distribution of values of the major and minor diameters of the femoral canal. The canal is observed to be elliptical in cross

of the Crowe IV femur, especially within the metaphysis, where the width of the canal was reduced by 25% in the mediolateral direction and 12% anteroposteriorly, compared with normal controls. The difference in rotational orientation caused the canal of the Crowe IV femur to look smaller in the lateral view but normal in the AP view. Consequently, the mediolateral and AP aspect ratio of the isthmus was 0.98 for the Crowe IV femurs versus 0.93 for the normal controls.

The shape of the canal in the coronal and sagittal projections also changed with the severity of dysplasia. In general, the dysplastic femurs were flared slightly less than the normal controls, with the average value of the canal flare index decreasing from 3.39 in the control group to 3.30 in Crowe I femurs, 3.34 in Crowe II/III femurs, and 2.68 in Crowe IV femurs (Figs 10,11). Within the midshaft region, the medullary canal of the normal femur approximated a cone with an included angle of 2.1° ± 1.4°. In comparison, the dysplastic femurs were significantly straighter (Crowe I, 1.8° ± 1.2°; $p = 0.012$; Crowe II/III, 1.6° ±1.1°; $p = 0.006$). The cross-sectional shape of the metaphysis was similar in the normal, Crowe I, and Crowe II/III femurs; however, Crowe IV bones were much narrower in the mediolateral direction compared with the AP direction. These bones also were more cylindrical, with a canal flare index of only 2.68 (versus 3.39 for normal controls; $p < 0.0001$), and a diaphyseal cone angle of 1.14°, approximately ½ of normal controls ($p = 0.0023$).

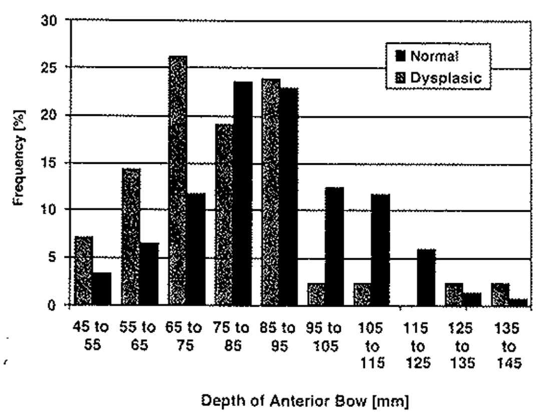

Fig 9. The graph shows the variation in the depth of the anterior bow of the medullary canal for the dysplastic femurs and the healthy controls.

Canal Rotation

Anteversion varied profoundly in all groups of femurs, including the controls, and ranged from −12° to 123° across the study population, although the majority of the cases (97%) were between 15° and 65°.

In the normal and dysplastic femurs, the rotational orientation of the metaphysis was approximately constant from the head center down to the level of the femoral neck osteotomy (the +35% level). Between this level, and 20 mm distal to the center of the lesser trochanter, the canal twisted abruptly, with the orientation of the endosteal cross section increasing by approximately 30° anteversion (Fig 12). From this point, down to the canal isthmus (approximately 90 mm), there was an additional, relatively uniform, increase in anteversion until the major diameter of the canal

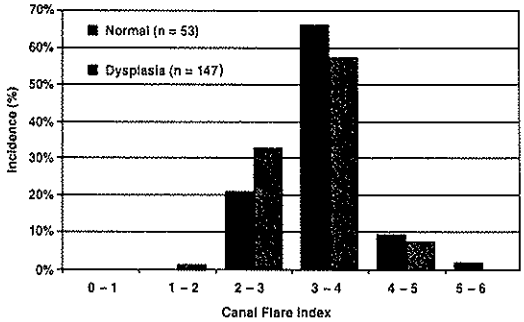

Fig 10. The graph shows the distribution of the canal flare index of the dysplastic femurs compared with healthy controls.

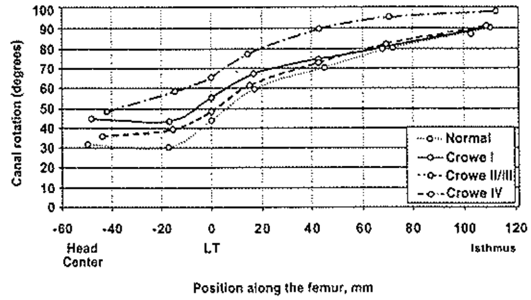

Fig 12. The variation in rotation of the medullary canal is shown as a function of location along the shaft of the femur for each group of dysplastic femurs and the healthy controls.

was oriented approximately perpendicular to the transcondylar axis of the distal femur.

With the exception of the Crowe IV femurs, there was no difference in the orientation of the canal at the level of the isthmus, regardless of the anteversion of the proximal femur. In the dysplastic femur, increased anteversion of the proximal femur resulted in less rotational twist in the medullary canal. Therefore, the average canal twist in the normal from the female femur was 48°, significantly larger than the Crowe I femur (36°), the Crowe II/III femur (42°), and the Crowe IV femur (37°).

DISCUSSION

Despite the prevalence of osteoarthritic secondary to congenital hip dysplasia, little is known about the morphologic characteristics of the dysplastic femur and the effects of this disorder on the geometry of the intramedullary canal. Previous studies have shown dramatic variations in the morphometry of dysplastic femurs with respect to their intracortical and extracortical geometry.[12] However, many studies have based their conclusions on limited observations, typically derived from small numbers of disparate cases of varying severity.[12] In several reports, anatomic parameters have been calculated for mixed groups of chronically dislocated hips (Crowe IV), intermingled with cases of lesser deformity with varying degrees of containment of the femoral head.[23] None of the previous authors has compared their observations with age- or gender-matched patients without a hip disorder. In addition, previous reports have been based on patients seen at one institution, without consideration of the effect of the racial makeup of the patient population, or the geographic variation in the severity of degenerative hip disease and underlying morphologic abnormalities.

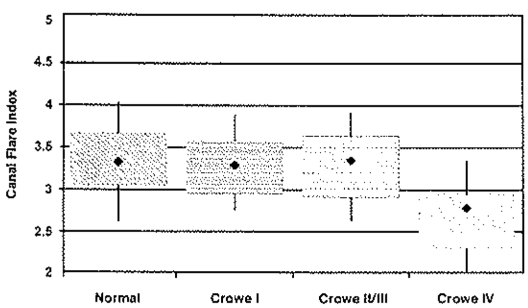

Fig 11. The canal flare index varies with the severity of hip dysplasia, as indicated by the Crowe index.

To overcome these shortcomings, the current study was done with collaboration among investigators at the Institute for Orthopedic Research and Education in Houston and three institutions in Japan (Chiba University, Osaka University Medical School, and Tokyo Medical and Dental University). This work was done using advanced methods of computer visualization and three-dimensional reconstruction of skeletal images derived from CT scans. The extraordinary number of individualized patient reconstructions makes this an unprecedented study, and several times larger than any previous report. In addition, identical methods were used to examine a large population of patients without hip dysplasia. These patients have acted as age- and gender-matched controls, allowing isolation of changes in skeletal morphologic characteristics attributable to dysplasia alone, independent of the confounding influence of demographic and geographic factors.

In general, the dysplastic femurs were smaller than the age-matched control femurs with narrower straighter and less tapered canals. As the severity of dysplasia increases, the anterior bow of the femur is displaced farther distally, leaving a longer segment of the canal for engagement with a straight stemmed prosthesis. A surprising observation was the prevalence of femurs with a high anterior bow, defined as 75 mm or less from the center of the lesser trochanter. In the population studied, this group of femurs made up 48% of the normal controls, 26% of the Crowe I femurs, 21% of Crowe II/III femurs, and 13% of Crowe IV femurs. Because many patients with CHD eventually have THR, it is instructive to examine the challenge that a proximal anterior bow presents to the joint replacement surgeon. In the average femur from a female, the femoral neck osteotomy is located 15 to 20 mm above the center of the lesser trochanter, so that the maximum length of a straight cylindrical prosthesis that can be implanted in a canal with a bow at the 75 mm level is 90 to 95 mm before cortical impingement occurs. Because most straight cementless prostheses are at least 115 mm in length, diaphyseal fractures and undersizing of the femoral component represent significant risks when joint replacement is done in the patient with dysplasia with an increased incidence of postoperative complications and suboptimal clinical outcomes. Although it is possible to reduce the incidence of these problems by aggressive canal reaming and even a transcortical osteotomy, a preferable approach would seem to be selection of asymmetric prostheses of 90 to 100 mm in length tapered to minimize the risk of impingement. This approach, pioneered by Sugano and Ohzono in Osaka, has been shown to lead to improved implant fit and stability without any compromise in clinical results.[21]

The current study extends the observations of many previous authors concerning exaggerated anteversion of the dysplastic femur. The analytical tools used in this study showed that the increased anterior offset of the dysplastic femur is generated by twisting of the entire proximal third of the bone in an anterior direction. In the medullary canal, this rotation is distributed from the inferior border of the femoral head to the level of the canal isthmus. At the level of the isthmus, there is no significant difference between normal and dysplastic femurs. In both cases, the major axis of the canal is oriented in an AP direction, approximately 90° to the posterior condylar axis of the distal femur.

This anatomic observation has several important clinical implications. Orthopaedic surgeons appreciate the fact that, during radiographic examination of the hip, the neck-shaft angle of the femur and the medial offset of the femoral head only are depicted accurately if the femoral neck is oriented parallel to the xray cassette. In the case of the dysplastic femur, in which anteversion is exaggerated, rotational orientation dramatically affects not only the appearance of the proximal femur, but the size and shape of the canal. Moreover, as the canal is twisted, the elliptical shape of the isthmus does not lie in the plane of the neck, but rather at 30° to 60° to the sagittal and coronal planes. Consequently, the minor axis of the isthmus appears on neither the AP nor the lateral radiograph. Thus measurements of canal size taken from the AP radiograph will overestimate the minimum diameter of the canal by as much as 2 mm. This explains why it often is difficult to select prostheses to fit the dysplastic canal, and why surgeons have favored the use of undersized cemented components that allow greater latitude intraoperatively.

One potential limitation of the present study is the possibility that conclusions derived from a Japanese population may not be generalized to all patients with hip dysplasia. In fact, if the femurs of middle-aged women of Japanese and

American origin without degenerative joint disease are compared carefully, an extraordinary similarity between external and intramedullary dimensions is found, with typical differences less than 3%. These femurs do differ in one significant respect, in that the femoral neck of the Japanese female is slightly less vertical, and has significantly more anteversion than its American counterpart. This speaks to the importance of an age- and gender-matched control group. Nonetheless, as the authors have studied the effects of hip dysplasia relative to normal controls, the conclusions of this study are expected to be universally applicable in terms of the relative impact of joint subluxation and dislocation on changes in femoral morphology.

Several surgical solutions have been proposed to correct the rotational deformity of the dysplastic femur in an attempt to restore the normal biomechanics of the hip. Derotational osteotomies of the proximal femur have been advocated for this purpose, however, as the twist of the anteverted femur is distributed from the lesser trochanter to the isthmus, the local deformity at any one level must be overcorrected to produce the desired displacement of head position. In cases where arthroplasty is necessary, conventional femoral stems are difficult to fit to the femur, despite the fact that the cross-sectional shape of the metaphysis is relatively normal in all but dislocated (Crowe IV) femurs. However, the twist in the canal and the change in canal taper necessitates the use of specialized implants specifically designed for the anteverted femur. An additional consideration is the acetabulum, which in the more dysplastic cases (typically Crowe III), often is shallow and unsuitable for bone grafting. This leads to high placement of the acetabular component, necessitating cephalad displacement of the prosthetic head on the femoral prosthesis.

In view of these challenges, many authors have recommended cemented femoral components, of miniature and modified designs, for use in the dysplastic femur.[13,14,16,19,27,30] Although the results of some series are encouraging, the canals of many patients with dysplasia are too narrow for a cement mantle of adequate thickness without compromising the strength and rigidity of the femoral component. Moreover, cemented monolithic components do not allow correction of the excessive anteversion of many dysplastic femurs without compromising the cement mantle. In view of these considerations, there has been increasing interest in the use of custom implants to allow optimal fit and fill of the complex dysplastic canal.[1,24,25] However, this solution requires significant lead time and is not practical in cases where the position of the acetabular component may be adjusted intraoperatively.[14] At present, more attractive options are modular prostheses and cementless implants that have been designed specifically to accommodate the abnormal morphologic characteristic of the dysplastic femur.[5,10,20,23]

Based on the results of the current study, we think that greater attention should be given to the morphologic characteristics of normal and dysplastic femurs in the middle-aged female patient. These findings, and those of earlier studies, indicated that prosthetic devices primarily designed for older individuals of larger anatomy do not fit the femora of younger patients who are smaller, or have hip dysplasia. Furthermore, in cases with excessive anteversion, the concomitant twist of the femoral canal makes joint replacement doubly difficult. Hopefully, the knowledge gained through this study will provide greater insight into the morphologic characteristics of the dysplastic femur and the challenges confronting the joint replacement surgeon.

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