The morphology of the femur in developmental dysplasia of the hip

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We studied the morphometry of 35 femora from 31 female patients with developmental dysplasia of the hip (DDH) and another 15 from 15 age- and sex-matched control patients using CT and three-dimensional computer reconstruction models. According to the classification of Crowe et al 15 of the dysplastic hips were graded as class I (less than 50% subluxation), ten as class II/III (50% to 100% subluxation) and ten as class IV (more than 100% subluxation).

The femora with DDH had 10° to 14° more anteversion than the control group independent of the degree of subluxation of the hip. In even the most mildly dysplastic joints, the femur had a smaller and more anteverted canal than the normal control. With increased subluxation, additional abnormalities were observed in the size and position of the femoral head. Femora from dislocated joints had a short, anteverted neck associated with a smaller, narrower, and straighter canal than femora of classes I and II/III or the normal control group.

We suggest that when total hip replacement is performed in the patient with DDH, the femoral prosthesis should be chosen on the basis of the severity of the subluxation and the degree of anteversion of each individual femur.

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Developmental dysplasia of the hip (DDH) is the most common underlying condition leading to secondary osteoarthritis of the hip, although the incidence of the latter varies on a regional and ethnic basis. In the absence of degenerative changes, femoral and/or pelvic osteotomies are often performed to correct DDH in an attempt to restore coverage of the femoral head. In advanced degenerative disease in the adult, total hip arthroplasty is done to eliminate subluxation and restore the normal position of the abductors with respect to the centre of the joint. This can only be successfully achieved if the nature and severity of the preoperative deformity are fully appreciated.

There have been few detailed studies of the morphometry of the dysplastic femur. It is well known that it often has a narrow medullary canal and increased anteversion, but the differences in the size and shape between normal and dysplastic femora have not yet been quantified. Previous studies have reported dimensional parameters derived from plain radiographs or CT of patients with DDH of varying degrees of severity, but without corresponding control groups. The size and shape of the human femur, however, vary with the gender, age, stature and ethnic background of the individual and it is not possible to isolate the effect of dysplasia on its shape. The degree of subluxation of the hip also leads to significant alterations in the shape of the femur because of profound changes in the magnitude and direction of the joint reaction force.

Because of the anatomical abnormalities of the dysplastic femur, it is widely believed that if total hip replacement is performed using conventional designs of femoral prostheses, the centre of the femoral head will not be restored to an acceptable position. This has led to the increased use of customised prostheses and the emergence of implants specifically designed for DDH. Since the anatomical abnormalities present are thought to increase with the severity of subluxation of the hip, the technical difficulty in performing joint replacement and the appropriate design of a femoral prosthesis may be related to the severity of the disease by its effect on the morphology of the dysplastic femur.

Our aim was to evaluate the hypothesis that the three-dimensional anatomy of the femur with DDH differs fundamentally from that of the normal femur and is related to the degree of subluxation of the hip.
Patients and Methods

We studied 35 femora from 31 adult female patients with DDH who represented variable degrees of subluxation. According to the classification of Crowe et al, 15 hips were class I (less than 50% subluxation) (Fig. 1a), ten class II or III (50% to 100% subluxation) (Fig. 1b) and ten class IV (more than 100% subluxation) (Fig. 1c). Eight patients in class I and class II/III had had closed reduction of the hip during childhood and one patient in class I open reduction. In the remaining 22 patients subluxation or dislocation of the hip had been noticed after the age of three years and had remained untreated. None of these patients had had an osteotomy for treatment or correction of their hip disease. We excluded patients with radiological evidence of joint degeneration or total ischaemic necrosis of the femoral head.

The three groups were matched as closely as possible for age. The overall mean age was 54.7 ± 11.2 (SD) years (23 to 73); patients in class I had a mean age of 52.5 ± 12.6 years (23 to 73) compared with 53.4 ± 11.0 years for those in class II/III (31 to 70) and 59.4 ± 8.5 years for class IV (43 to 69) (p > 0.05, unpaired t-test). An additional group of 15 age-matched female patients (mean age 59.7 ± 14.9 years; range 20 to 78) served as a normal anatomical control group. They had undergone radiological investigation of non-traumatic osteonecrosis of the femoral head (8 patients) or rheumatoid arthritis (7 patients) and had at least one hip that was radiologically normal without collapse of the femoral head or erosive changes.

The mean height of the patients with DDH in class I was 152 ± 4.2 cm (146 to 160), in class II/III 150 ± 5.8 cm (143 to 157) and in class IV 147 ± 6.8 cm (138 to 157). That of the control group was 152 ± 6.8 cm (138 to 164). There was no statistically significant difference between the four groups except between classes I and IV (p = 0.02, unpaired t-test). The mean body-weight was 54 ± 4.2 kg (46 to 62) in class I, 54 ± 7.9 kg (38 to 68) in class II/III, 52 ± 7.3 kg (42 to 62) in class IV, and 54 ± 10.2 kg (36 to 76) in the control group. None of these differences was statistically significant. The average height and weight of the DDH and control groups were identical to published data for Japanese women of 50 to 59 years of age (152 ± 5.1 cm and 54 ± 8.0 kg).

Transverse images were obtained of each femur using a helical CT scanner (CT HiSpeed Advantage RP; GE, Milwaukee, Michigan) according to a standard CT protocol with a field of view of 34 cm. Each CT image was reconstructed using a standard bone algorithm (GE). Image data stored on an optical disc were converted to a tiff format of 512 × 512 matrix by a data conversion program (GE MOD/RPF; Image and Measurement, Tokyo, Japan) and a digital image analysis program (BrainImage; Kennedy Krieger Institute, Baltimore, Maryland) operating on a desktop computer (Power Tower Pro 225; Power Computing, Round Rock, Texas).

The hip and knee were fully extended with the lower limbs secured to the table with a below-knee splint which fixed the rotational position of the limb. Positioning was checked by anteroposterior and lateral scout views. Each femur was imaged using the following set of transverse scans: 1) contiguous 3 mm slices from the top of the femoral head to 2 cm below the lesser trochanter; 2) 3 mm slices at 10 mm intervals from 2 cm below the lesser trochanter to 157) and in class IV 147 ± 6.8 cm (138 to 157). That of the control group was 152 ± 6.8 cm (138 to 164). There was no statistically significant difference between the four groups except between classes I and IV (p = 0.02, unpaired t-test). The mean body-weight was 54 ± 4.2 kg (46 to 62) in class I, 54 ± 7.9 kg (38 to 68) in class II/III, 52 ± 7.3 kg (42 to 62) in class IV, and 54 ± 10.2 kg (36 to 76) in the control group. None of these differences was statistically significant. The average height and weight of the DDH and control groups were identical to published data for Japanese women of 50 to 59 years of age (152 ± 5.1 cm and 54 ± 8.0 kg).

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trochanter to 2 cm below the isthmus of the femoral canal; and 3) seven serial slices of 3 mm thickness through the femoral condyles.

A customised program was developed to reconstruct the image of each femur from the CT data and to allow calculation of dimensional and morphological variables. All the data could be extracted independently of the position of the patient during scanning and the orientation of the original CT slices with respect to the femur.

In the first stage of the bone reconstruction process the inner (endosteal) and outer (periosteal) contours of the femur were extracted using a Laplacian and Gaussian filter with a gradient thresholding. Specialised pattern recognition software was then used to partition the co-ordinate data into subsets describing the internal and external surfaces of six contiguous regions within each femur (the femoral head, the neck, the greater and lesser trochanters, the metaphysis and diaphysis and the femoral condyles).

Three-dimensional surface-splined models of each contiguous region were constructed and reorientated until the axis of the femoral shaft and the centre of head were located within the coronal plane with the femoral axis parallel to the vertical direction (Fig. 2). The following variables were calculated:

1) The centre and diameter of the femoral head, obtained from the sphere of best fit to data describing the surface of the head. Severely deformed regions of the femoral head were visually identified and eliminated from the calculation.

2) The height of the centre of the femoral head, defined as the vertical distance from the centre of the lesser trochanter (CLT) to the centre of the femoral head.

3) The medial offset of the femoral head, defined as the perpendicular distance from the medullary axis to the centre of the head.

4) The axis of the femoral neck, calculated as the line of best fit to the centroids of 1 mm slices taken through a central segment of the neck (length 21 mm) (Fig. 3).

5) The canal isthmus, defined as the point of minimum
cross-sectional area of the medullary canal.

6) The length of the femoral neck defined as the distance between two points on the neck axis located closest to the centre of the femoral head and the medullary axis, respectively.

7) The height of the greater trochanter, defined as the vertical distance from the CLT to the tip of the trochanter.

8) The mediolateral diameter of the medullary canal, measured at four levels within the canal: the 35% level (35% of the head centre height above the CLT), the level of the CLT, the –35% level (35% of the head centre height below the CLT), and the level of the canal isthmus. The maximum value of the mediolateral extracortical diameter of the diaphysis was also recorded.

9) The anteversion of the femur, defined according to Kingsley and Olmsted in a spatial co-ordinate system simulating placement of the femur on a flat surface. For this purpose, the three-dimensional model was positioned with the table plane (z-x plane) coincident with the posterior condyles and the most prominent posterior point of the greater trochanter. The axis of the femoral shaft was defined as the line connecting the centroids of a transverse section through the femur at the base of the lesser trochanter and a section taken through the distalcondyles at the point of greatest anteroposterior width of the femur. Femoral anteverision was defined as the angle formed between the axis of the neck and the table plane when viewed along the femoral axis (Fig. 4).

10) The canal flare index, calculated as the ratio between the mediolateral width of the medullary canal at the 35% level and at the canal isthmus.

11) The major axis angle, defined as the angle between a line connecting the longest transverse diameter of the canal, was measured at the same level as the mediolateral diameter of the canal. This parameter was selected as a measure of canal rotation.

We performed statistical analysis on the morphological variables of the four groups. Initially, we tested the distribution of each variable for normality using the Shapiro-Wilk W test. For normally distributed variables, differences between groups were analysed by ANOVA followed by the unpaired t-test for multiple pair-wise comparisons of all significant variables (p < 0.05). The Kruskal-Wallis test was applied to all variables that were not normally distributed, followed by the Mann-Whitney test for non-parametric post-hoc comparisons. In view of the large number of comparisons performed in this study (102), the p value for a statistically significant difference between two variables was set at 0.005. Although this threshold provides a good balance between type-I and type-II errors, the

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Table I. Mean (± so) dimensional parameters in each group

<table>
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<tr>
<th></th>
<th>Control</th>
<th>I</th>
<th>II or III</th>
<th>IV</th>
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<tbody>
<tr>
<td>Height of femoral head (mm)</td>
<td>44.2 ± 5.4</td>
<td>45.7 ± 6.5</td>
<td>36.3 ± 7.2</td>
<td>39.0 ± 4.9</td>
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<tr>
<td>Diameter of femoral head (mm)</td>
<td>44.1 ± 2.0</td>
<td>44.9 ± 1.9</td>
<td>50.9 ± 5.3</td>
<td>42.2 ± 6.1</td>
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<tr>
<td>Neck length (mm)</td>
<td>47.5 ± 5.5</td>
<td>43.0 ± 3.0</td>
<td>38.0 ± 5.3</td>
<td>35.7 ± 4.4</td>
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<tr>
<td>Height of greater trochanter (mm)</td>
<td>54.3 ± 4.0</td>
<td>53.8 ± 3.6</td>
<td>50.3 ± 4.9</td>
<td>55.8 ± 5.8</td>
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<tr>
<td>Isthmus position (mm)</td>
<td>106.7 ± 14.2</td>
<td>98.5 ± 11.8</td>
<td>105.6 ± 8.3</td>
<td>93.5 ± 10.8</td>
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<tr>
<td>Mediolateral extracortical diameter of the diaphysis (mm)</td>
<td>25.3 ± 1.8</td>
<td>23.8 ± 1.5</td>
<td>22.6 ± 1.7</td>
<td>21.6 ± 1.5</td>
</tr>
<tr>
<td>Median lateral canal width (mm)</td>
<td>At 35% of head centre height above CLT</td>
<td>41.7 ± 2.8</td>
<td>38.6 ± 3.1</td>
<td>40.9 ± 3.1</td>
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<tr>
<td>At CLT</td>
<td>29.9 ± 3.4</td>
<td>26.5 ± 2.2</td>
<td>30.9 ± 3.3</td>
<td>23.2 ± 4.1</td>
</tr>
<tr>
<td>At 35% of head centre height below CLT</td>
<td>23.7 ± 4.3</td>
<td>19.8 ± 2.4</td>
<td>24.8 ± 4.0</td>
<td>18.5 ± 4.1</td>
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<tr>
<td>At isthmus</td>
<td>12.8 ± 2.6</td>
<td>9.8 ± 0.9</td>
<td>10.6 ± 2.0</td>
<td>10.4 ± 1.5</td>
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<tr>
<td>Canal flare index</td>
<td>3.4 ± 0.7</td>
<td>4.0 ± 0.5</td>
<td>3.9 ± 0.7</td>
<td>3.0 ± 0.5</td>
</tr>
<tr>
<td>Anteroposterior canal width at isthmus (mm)</td>
<td>16.3 ± 3.1</td>
<td>13.0 ± 1.9</td>
<td>14.7 ± 2.0</td>
<td>13.6 ± 2.4</td>
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<td>Neck-shaft angle (degrees)</td>
<td>125.8 ± 6.3</td>
<td>127.9 ± 8.9</td>
<td>123.9 ± 5.2</td>
<td>117.7 ± 6.6</td>
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<td>Anteversion (degrees)</td>
<td>22.6 ± 10.6</td>
<td>34.0 ± 16.0</td>
<td>32.8 ± 14.4</td>
<td>37.0 ± 5.4</td>
</tr>
<tr>
<td>Major axis angle (degrees)</td>
<td>At 35% of head centre height above CLT</td>
<td>15.2 ± 10.4</td>
<td>28.4 ± 17.1</td>
<td>29.3 ± 17.3</td>
</tr>
<tr>
<td>At CLT</td>
<td>35.2 ± 8.8</td>
<td>46.1 ± 14.4</td>
<td>43.2 ± 14.2</td>
<td>47.5 ± 8.0</td>
</tr>
<tr>
<td>At 35% of head centre height below CLT</td>
<td>39.6 ± 10.2</td>
<td>54.8 ± 13.2</td>
<td>49.9 ± 14.9</td>
<td>55.7 ± 10.4</td>
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<tr>
<td>At isthmus</td>
<td>70.2 ± 12.8</td>
<td>68.7 ± 13.1</td>
<td>72.9 ± 10.3</td>
<td>67.3 ± 12.8</td>
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Fig. 4

A top view of the femur orientated within the table-top co-ordinate system showing the centre of the femoral head (A), the axis of the medullary canal (B) and the axis of the femoral neck (C).
chance of at least one spurious significant difference was 40% (1-\([1-0.005]\)^{10^2}).

**Results**

The mean length of the femur, as measured on the antero-posterior scout view was 400 ± 15 mm (382 to 434) for the control group, compared with an overall mean of 391 ± 19 mm (353 to 440) for the dysplastic groups (p > 0.05, unpaired t-test). The mean CE angle was 10 ± 5.8° (0 to 18) for class I and 28 ± 5.8° (20 to 38) for the control group. The mean Sharp angle was 47.9 ± 3.2° (43 to 52) for class I and 39.3 ± 3.8° (29 to 44) for the control group.

Tables I and II give the measured variables in the four groups and the p values for pair-wise comparisons for each variable. The mean shape of the femur in each group is shown in Figure 5. There was no significant variation between groups in terms of the height of the centre of the head and the canal orientation at the isthmus. There were few differences between femora in class I and in the control group but the medullary canals of class-I femora were shorter and were more tapered than those of the age-matched control group as indicated by differences in the canal flare index (p < 0.05). The inclination of the femoral neck was similar in class-I and control femora, but the femoral neck and the medullary canal were more anteverted at all levels proximal to the medullary isthmus. With the exception of the major axis angle at the isthmus, all of these differences were statistically significant (Tables I and II).

In the DDH groups, the height of the centre of the femoral head, the neck length, and the extracortical mediolateral diameter at the isthmus decreased with subluxation of the hip (Table I). The widths of the medullary canal at the 35% level, at the CLT, and at the −35% level were significantly smaller in class IV than in class I, class II/III, and the control group (Table II and Fig. 6). The width of the canal at the isthmus was comparable in all three DDH groups. Class-IV femora had the straightest canals, compared with class-I and class-II/III femora (Figs 6 and 7), as indicated by the values of the canal flare index (3.0 v 4.0 and 3.9, respectively). The canal taper of class I, class II/III, and the control femora were similar above the 35% level.

The average neck-shaft angles of the control and dysplastic femora were very similar, although there were some differences in the distributions of both groups (p = 0.371) (Fig. 8). Overall, the incidence of coxa valga (neck-shaft angle >135°) was 7% in the normal femora and 9% in the DDH group, while coxa vara (neck-shaft angle <115°) occurred in none of the normal femora but in 11% of the dysplastic group. Within the DDH femora, the neck inclina-

![Fig. 5](image-url)
tion decreased with increasing severity of subluxation, with an increased incidence of coxa vara in the femora of class IV, compared with class I or class II/III (p < 0.01 and p < 0.05) (Figs 2 and 7).

The femora with DDH had anteversion on average of more than 10 to 14° of that of the age-matched control group. In addition, the incidence of excessively anteverted femora (anteversion >40°) was only 7% in the normal femora compared with 23% in femora with DDH (Fig. 9). The anteversion in all three DDH groups was comparable. Moreover, the axial variation in the rotational orientation of the medullary canal was remarkably similar for both the normal and DDH femora. This supports the conclusion that the observed differences in anterior offset of the femoral head were due to differences in canal torsion, primarily between the isthmus and the −35% level of the canal. The change in rotational orientation of the canal above the 35% level was similar in class I and class II/III compared with the normal control group.

Discussion

Previous studies on the morphology of the femur in adults with DDH have made qualitative and clinical observations...
Fig. 8
Bar chart of the neck-shaft angle of the normal and dysplastic femora.

Fig. 9
Bar chart of the neck anteversion of the normal and dysplastic femora.

Fig. 10
Variation of the torsional alignment of the medullary canal at the 35% level, at the centre of the lesser trochanter (CLT), at the –35% level and at the isthmus. Corresponding values of the mean anteversion of each group are included for comparison.
on the basis of plain radiographs. A common characteristic of DDH is an unusually small femoral head associated with a short femoral neck, which is often markedly antverted. The dysplastic femur has also been shown to have a straighter, more tapered canal with an unusually narrow medullary isthmus and the neck-shaft angle is more valgus than that of the normal femur, resulting in a medial cortex of a larger radius.

Few previous studies have used CT and three-dimensional reconstruction to describe fully the deformities associated with hip dysplasia. Robertson et al were the first to use these techniques to examine the geometry of the proximal femur in 24 Japanese adults with DDH. Their findings led to the development of an average model of the dysplastic femur but their study was based on a heterogeneous group of male and female patients with widely varying degrees of subluxation. Furthermore, as there was no control group, they could only draw conclusions regarding abnormalities of the shape and dimensions of the dysplastic femur on the basis of anatomical parameters derived from normal femora of Western populations.

In our study, all the groups were matched for age and gender since significant changes in the shape of the proximal femur have been related to these variables. All our measurements were derived from three-dimensional reconstructions of individual femora, based upon CT data obtained using a high-speed helical scanner. This allowed us to compare the morphometry of normal femora with each of the dysplastic groups. Our findings showed that although the stature of the patients and the overall length of their femora were not significantly different from those of the normal control group, even the femora in class I had significant anatomical abnormalities, including a shorter femoral neck and a narrower diaphysis and intramedullary canal. Similar findings were observed in patients with more severe dysplasia and subluxation in whom femoral hypoplasia was a common observation.

Our study also showed that dysplastic femora had a significant increase in anteverision of the femoral neck. Although this was highly variable, mildly dysplastic femora (class I) had anteverision of 12° more than that of the normal control group, with anteverision of individual cases exceeding 60°. Class-II/III and class-IV femora also showed similar abnormalities with anteverision of 10 to 14° more than normal. When we compared the canal orientation of each group, we found that the increased torsion of the DDH femora arose within the diaphysis between the lesser trochanter and the isthmus (Fig. 10). This finding supports the theory that the excessive anteverision of the DDH femur is due to abnormal internal rotation of the limb in utero because femoral anteverision has been shown to decrease throughout childhood at a relatively constant rate as part of the normal process of skeletal maturation, even in cases of DDH. We therefore expect that, at birth, the anteverision angles of our DDH patients were even greater than our mean value of 34.6°.

The cross-sectional shape of the medullary canal was remarkably similar in all four groups. The major canal axis at the isthmus was orientated in the same direction in the DDH and normal femora and the AP diameter of the canal was larger than the ML diameter. This finding contradicts the observation of Mendes who stated that the shape of the DDH canal was narrower in the frontal plane than in the sagittal plane as a result of residual or excessive anteverision of the proximal femur and the femoral neck.

It is widely believed that coxa valga is typically present in the DDH femur, but we found no significant difference in the neck-shaft angle of class I and control femora. On the contrary, the mean inclination of the femoral neck decreased slightly with increasing severity of subluxation (Table I) and therefore there were significantly more cases of coxa vara in patients classified as class IV than in the control group. The impression that the DDH femur has a more valgus neck inclination is probably due to the normal effect of anteverision on the appearance of the proximal femur as projected on a standard AP radiograph. As the neck of the average DDH femur is orientated at 35° to the coronal plane, the AP radiograph gives an oblique view of the proximal femur, with significant foreshortening of the neck.

We have shown that the Crowe classification is a useful guide for the selection of femoral prostheses. In cases of class I, II or III subluxation, conventional designs of femoral stem may be acceptable in many cases, provided that due consideration is given to the small size of many femora in DDH. In cases of more than 40° of anteverision, however, a corrective osteotomy, a retroverted insertion of a cemented stem, a customised implant, or a prosthesis with a modular neck that allows adjustment of anteverision may be required. In cases of class IV, the canal is straight and narrow and a straight stem with little proximal medial curvature should be used, even if a hip replacement together with a segmental osteotomy and preservation of the femoral neck are needed.

We suggest therefore that when total hip replacement is performed in the DDH patient, the femoral prosthesis should be chosen on the basis of the severity of subluxation of the hip and the degree of anteverision of each individual femur.

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References


