Three-dimensional analysis of the proximal femur in patients with slipped capital femoral epiphysis based on computed tomography.

Kordelle J, M.D.1), Millis M, M.D.2), Jolesz FA, M.D.1), Kikinis R, M.D.1), Richolt JA, M.D.3)

Study conducted at the Brigham & Women's Hospital, Surgical Planning Laboratory, Harvard Medical School, Boston, Massachusetts, USA

From
1) Surgical Planning Laboratory, Department of Radiology, Brigham & Women's Hospital, Harvard Medical School, Boston, USA
2) Department of Orthopedic Surgery, Children's Hospital, Harvard Medical School, Boston, USA
3) Department of Orthopedic Surgery, University Hospital of Frankfurt Frankfurt/Main, Germany

Address correspondence and reprint request to
Dr. med. J. Kordelle
Department of Orthopedic Surgery
University Hospital of Giessen
Paul-Meimberg-Str. 3
35385 Giessen
Germany
Phone: 01149 641 99 42900
Fax: 00149 641 99 42999
E-mail: jeko@bwh.harvard.edu

Running title:
Geometry of the proximal femur in patients with SCFE.

Summary
A three-dimensional analysis based on CT was performed to study the 3D geometry of the proximal femur in cases of slipped capital femoral
epiphysis (SCFE). For this purpose, a new interactive software was developed to analyze hip joint geometry using three-dimensional models without pelvis tilting and projected errors. 22 patients, 8 females and 14 males, with a total of 30 slipped capital femoral epiphsyses were reviewed. In the affected hips we observed a reduced femoral anteversion of 7.0° (versus 12.7°) and a reduced femoral shaft neck angle of 134.2° (versus 141.0°). In response to these results, we suggest that a slipped capital femoral epiphysis is associated with a reduced femoral anteversion and a reduced femoral shaft neck angle.

Keywords
slipped capital femoral epiphysis (SCFE) - femoral anteversion - femoral shaft neck angle (CCD) - preventive in-situ-pinning - 3D

Introduction
The physiological development of the proximal femur depends on a balance of growth between the epiphysis and the growth plates of the greater trochanter and the femoral neck isthmus. In cases of SCFE the capital femoral epiphysis, including the femoral head, is displaced from the metaphysis. Usually the femoral head is tilted in a posteroinferior position in relation to the femoral neck whereas a valgus slip was rarely observed [15, 16]. Shear forces, influenced by body weight, muscle forces, and abnormal femoral orientation, appear to play a major role in the development of SCFE [1, 2, 3, 10, 13]. Some authors reported an association between SCFE and abnormal femoral angulation [4, 8, 9, 14, 17, 18, 19]. However, to our knowledge, no three-dimensional analysis of the geometry of the proximal femur without pelvis tilting and projected errors was performed. In this article, a new concept for angular measurements in
cases of SCFE based on three-dimensional (3D) computer models is illustrated.

**Material and Methods**

Three-dimensional models based on CT data sets of 22 patients with thirty slipped capital femoral epiphyses were reviewed. The computed tomography data sets were achieved with patients in supine position and consisted of 2-5 mm contiguous, axial slices through the hip joint. Three-dimensional models were constructed based on "The Visualization Toolkit" (kitware, Inc.; Clifton Park; NY 12065; USA).

Measurement of hip joint geometry was performed by using a newly developed interactive software to determine projected angles. The measurement tool consists of two elements. The end of the tool is provided with a plane to facilitate the definition of the orientation of the acetabulum and the epiphysis. The purpose of the tool's axis is to define the longitudinal axis of an anatomical structure (e.g. femoral shaft axis). The three-dimensional model and the measurement tool can be freely shifted and rotated in all planes. A phantom scan was performed to validate the accuracy of the tool. The measurements of the 3D digital model are compared with the measurements on the real phantom. The average difference (± one standard deviation) for the anteroposterior angle is -0.02° ± 0.84° and +0.06° ± 1.16° for the torsion measurement. To analyze the three-dimensional geometry of the proximal femur we used four axes described as follows. The femoral shaft axis was defined as a line between the axial center of the femur underneath the lesser trochanter to the center of the axial condyle region (Fig. 1).
The femoral neck axis was determined as a line through the center of the connection A-B and C-D in the horizontal and vertical plane (Fig. 2).

The orientation of the epiphyseal axis was defined as illustrated in Figure 3.
Figure 3. Epiphyseal axis.

A line between the most dorsal points of the medial and lateral condyles was designated as the condyle axis (Fig. 4).

Figure 4. Condyle axis.

The shaft neck angle ($\alpha$) was defined as the angle between the femoral shaft axis and the femoral neck axis (Fig. 5).
Figure 5. Shaft neck angle ($\alpha$).

The anteversion of the femur ($\beta$) was determined as the angle between the condyle axis and the femoral neck axis (Fig. 6).

Figure 6. Femoral neck anteversion ($\beta$).

Furthermore, the femoral shaft axis was used to measure the shaft epiphysis angle ($\gamma$) (Fig. 7).
The epiphyseal anteversion ($\delta$) was measured between the condyle axis and the epiphyseal axis (Fig. 8).

**Figure 7.** Shaft epiphysis angle ($\gamma$).

**Figure 8.** Epiphyseal anteversion ($\delta$).
The degree of inferior slip was calculated as shaft neck angle minus shaft epiphysis angle. Posterior slip was determined as the difference between the femoral anteversion and epiphyseal anteversion.

Results

We reviewed 22 patients: 8 females and 14 males with 30 slipped capital femoral epiphyses. The mean age was 13.4 (9.3 - 16.8). The right hip was affected in ten cases and the left in twenty cases. In 27 cases, we found a posteroinferior tilt of the capital femoral epiphysis. A slip in just one plane was found in three cases. The 3D analysis showed that the mean inferior slip was 18.0 degrees (range: 2.2° - 47.9°) and the mean posterior tilt was 50.7 degrees (range: 4.1° - 87.9°).

Compared with the unaffected hips, the shaft-neck angle of the affected hips was reduced by an average of 6.8°. Femoral anteversion (β) of the affected hips was on average 5.7° less than that of the unaffected hips (Table 1).

Table 1. Three-dimensional geometry of the proximal femur in patients with slipped capital femoral epiphysis: affected versus unaffected.

<table>
<thead>
<tr>
<th></th>
<th>affected</th>
<th></th>
<th></th>
<th>unaffected</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>Mean</td>
<td>Range</td>
<td>No.</td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>Shaft-Neck-Angle (α)</td>
<td>30</td>
<td>134.2’</td>
<td>(110.9’ - 153.0’)</td>
<td>14</td>
<td>141.0’</td>
<td>(122.6’ - 149.5’)</td>
</tr>
<tr>
<td>Femur-Version (β)</td>
<td>30</td>
<td>7.0°</td>
<td>(-13.4’ - 24.6’)</td>
<td>14</td>
<td>12.7°</td>
<td>(-10.4’ - 34.0’)</td>
</tr>
<tr>
<td>- Anteversion</td>
<td>21</td>
<td>12.8°</td>
<td>(0.1’ - 24.6’)</td>
<td>11</td>
<td>18.3°</td>
<td>(3.2’ - 34.0’)</td>
</tr>
<tr>
<td>- Retroversion</td>
<td>9</td>
<td>6.5°</td>
<td>(7.0’ - 13.4’)</td>
<td>3</td>
<td>8.1°</td>
<td>(10.4’ - 6.0’)</td>
</tr>
<tr>
<td>Shaft-Epiphysis-Angle (γ)</td>
<td>30</td>
<td>116.2’</td>
<td>(83.1’ - 153.0’)</td>
<td>14</td>
<td>130.6’</td>
<td>(100.1’ - 148.3’)</td>
</tr>
<tr>
<td>Epiphysis-Version (δ)</td>
<td>30</td>
<td>-43.7°</td>
<td>(-96.5’ - 1.3’)</td>
<td>14</td>
<td>-4.8°</td>
<td>(-19.7’ - 13.5’)</td>
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<tr>
<td>- Anteversion</td>
<td>1</td>
<td>1.3°</td>
<td>-</td>
<td>5</td>
<td>10.6°</td>
<td>(6.8’ - 13.5’)</td>
</tr>
<tr>
<td>- Retroversion</td>
<td>29</td>
<td>45.8°</td>
<td>(6.9’ - 96.5’)</td>
<td>9</td>
<td>13.4°</td>
<td>(2.7’ - 19.7’)</td>
</tr>
</tbody>
</table>
We found no correlation, between the shaft-neck-angle (α) and the degree of inferior slip (Spearmann Rank Correlation Test: p: 0.19) or between the femoral anteversion (β) and the degree of posterior slip (Spearmann Rank Correlation Test: p: 0.59).

**Discussion**

Plain radiographs are still used for angular measurements in cases of SCFE. Angular measurements on plain radiographs suffer from projected errors caused by distorted positioning and superposition of anatomical structures. Geometry of the proximal femur can be accurately measured by 2DCT images [4, 18]. In general, cross-sections through the hip and through the knee condyles are taken. This makes it possible to determine torsion of the femoral neck and physeal torsion and does not suffer from projectional distortion due to its cross-sectional imaging. However, it is difficult to define the femoral neck axis on 2DCT images in patients with a severely deformed femoral neck [5, 11]. In addition, CT images of the hip region in general provide only axial cross-sections and therefore without further processing of these cross-sections this methodology does not allow definition of shaft neck angle and shaft physis angle.

The pathogenesis of slipped capital femoral epiphysis is probably a multifactorial event. Several studies have established the impact of biomechanical factors [2, 4, 7, 10, 13, 19]. Shear forces caused by changed femoral geometry depending on the level of activity may lead to a slip of the femoral epiphysis [2]. In a 2DCT study Gelberman et al found a reduced degree of femoral anteversion of 1° (±8°) in 25 patients with 39 unilateral or bilateral SCFE in comparison to the predicted mean amount for individuals of the same age and to the unaffected contralateral hips (n=11) [4].
Stanitiski et al reported a relative femoral retroversion of 10.7° in 7 cases of SCFE [18]. Earlier studies reported that varus deformities of the femur are also associated with SCFE [9, 12, 17]. In correspondence with these findings we likewise observed a reduced shaft neck angle (α) of 134.2 degrees and a reduced femoral anteversion (β) of 7.0 degrees on average in comparison to the contralateral unaffected hips.

Little is known regarding the redistribution of shear forces in the pathological geometry of the proximal femur. Pritchett et al observed in a three-dimensional force analysis that a reduced femoral anteversion of 10 degrees increases the shear forces by 3.3 times body weight during fast walking, which may cause a slip of the femoral epiphysis [13]. Chung et al demonstrated that epiphyseal shear forces and neck shaft-plate shaft angle are directly related and that a reduction of this angle of 10° may reduce the force necessary to produce a slip of the femoral epiphysis by approximately 17 percent [2]. An abnormal angulation of the proximal femur in both the sagittal and frontal planes as observed in this study is probably one reason for SCFE. Preventive fixation of the contralateral hip is discussed controversially. Hagglund et al. reported 9 % of SCFE were bilateral at the moment of diagnosis and 32 % became bilateral during adolescence (n=260) [6]. With regard to these findings the authors recommend preventive contralateral in-situ-pinning in patients with unilateral SCFE when an abnormal angulation of the contralateral proximal femur was found and the growth cartilage is still open.

**Conclusion**

3DCT studies of the hip in SCFE allow detailed analysis of the epiphysis and the femoral neck. The results demonstrate that SCFE is associated with
a reduced femoral anteversion and a reduced shaft neck angle. This should be taken into account when considering preventive in-situ-pinning of the contralateral unaffected hip.

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References


