Anatomical analysis and preoperative planning of correctional osteotomies in patients with Slipped Capital Femoral Epiphysis (SCFE).

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Summary

SCFE is defined as the slippage of the femoral head relative to the femoral neck along the proximal femoral growth plate. The femoral head shifts and rotates along the proximal end of the femoral neck usually posteriorly and inferiorly. The pathoanatomical findings are characterized by the changed relationship between the femoral head and femoral metaphysis and between the femoral head and the acetabulum. Furthermore, a reduced femoral anteversion [8, 28], a varus deformity of the femur [17, 23, 26], a shortening of the femoral metaphysis and an anterior metaphyseal prominence is regularly observed. This may lead to an impingement between the femoral metaphysis and the acetabular rim. Potential consequence of this complex three-dimensional deformity is pain, a reduced range of hip motion and an early degenerative joint disease [9, 16, 21]. In moderate and severe cases a redirectional femoral osteotomy is recommended. Different techniques as subcapital, base-of-neck, intertrochanteric and subtrochanteric osteotomies are described [1, 5, 6, 13, 14, 15, 18, 22, 25, 27]. These correctional osteotomies aim towards a reconstruction of the hip joint geometry to prevent early arthritic degeneration. Currently, the planning of a surgical treatment in these cases is based on measurements on antero-posterior and lateral plain radiographs. Relevant angle for planning of correctional osteotomies is the physis-shaft angle determined in both plains. These angles describe the degree of the slippage and thereby help the surgeon to indicate and plan a correctional osteotomy [13, 14, 27]. However, plain radiographs
are projectional images and therefore carry inaccuracies caused by the overlay of anatomical structures and an incorrect positioning of the patient. 3D reconstructions are more accurate and provide additional substantial information for the surgeon as for instance the anteversion of the acetabulum. The authors developed an interactive three-dimensional software to measure projected angles to analyse the geometry of the proximal femur and to determine the orientation of the acetabulum basing on three-dimensional reconstructions of CT data sets. Furthermore, a program was developed to simulate different techniques of osteotomies and to evaluate the postoperative range of hip motion and the hip joint geometry. Accurate three-dimensional measurements, additional anatomical information, the possibility to simulate different techniques of osteotomies and to evaluate the simulated postoperative result enables the surgeon, with regard to the clinical findings, to decide for the best surgical treatment.

Introduction

Slipped capital femoral epiphysis (SCFE) is the most common cause of adolescent hip disease (4-5/100,000) and describes the change in the relationship between the femoral epiphysis and the femoral neck. Usually the femoral head is tilted in a postero-inferior position in relation to the femoral neck whereas a valgus slip is rarely observed. Several factors, for instance endocrine disorders [12, 20] or genetic factors [10, 11] have been discussed as etiologic agents. Shear forces, influenced by body weight, muscle forces, and abnormal femoral orientation, appear to play a major role in the development of SCFE [3, 4, 7, 19, 24]. Clinical findings are usually pain and a reduced range of motion of the hip joint (flexion, abduction and internal rotation). Moderate and severe cases of SCFE may lead to a secondary coxarthrosis [9, 16, 21]. Potential reasons for the early degenerative joint disease is incongruence between both joint partners, a changed load transmission from the femur to the acetabulum and an impingement between the acetabular rim and the femoral metaphysis. The impingement may erode the acetabular labrum and lead to an unphysiological bone-cartilage contact between the femoral metaphysis and the acetabulum. In addition, when the hip is flexed or abducted the impingement may lead to a levering of the femoral head out of the acetabulum. Common goal of all different techniques of redirectional osteotomies of the proximal femur is to reconstruct the hip joint geometry. The successful reconstruction of the hip joint should improve the hip
function and prevent a secondary degenerative joint disease. Several authors recommend different methods of reorientation osteotomies as subcapital, base of neck, intertrochanteric and subtrochanteric techniques [1, 5, 6, 13, 14, 15, 18, 22, 25, 27] (fig. 1).

![Osteotomies of the proximal femur](image)

**Figure 1.** Different techniques of osteotomies of the proximal femur.

A preferred surgical technique is the three-dimensional intertrochanteric flexion valgisation and internal rotation osteotomy introduced by Imhaeuser 1957 [14]. The planning of this correctional osteotomy based on the physis-shaft angle, measured on anterior-posterior and lateral plain radiographs. This angle describes the degree of the slippage and thereby the amount of surgical correction, as illustrated in figure 2.
Errors caused by the overlay of anatomical structures and an incorrect positioning of the patient reduces the accuracy of these measurements. Important information as the acetabular anteversion is not measurable.

The presented 3D-software concept was developed to improve the accuracy of angular measurements, to enable the surgeon to evaluate the postoperative results (ROM and geometric analysis) and to provide the possibility to simulate different techniques of osteotomies.

**Material and methods**

*Three-dimensional reconstruction*

Cross-sectional images are the basis for the proposed system. The scan should cover the area between acetabulum and minor trochanter with contiguous 2-5 mm slices. In addition, one cross-section of the femoral knee condyles is acquired. During the 3D measurement, this cross-section provides important information about the rotation of the femoral neck relative to the knee. Further post-processing was performed on Sun Computers, Palo Alto, CA, USA. Goal of the post-processing is to delineate the structures of interest within the scanned volume. This step is called segmentation. Initial segmentation of femur and pelvis is done with commonly used intensity thresholding techniques and manually operator interaction. The final segmented volume contains pelvis, femoral head, proximal femoral metaphysis and a cross-section of the condyle, for both sides. The segmented files are reconstructed to 3D models using marching cubes, an algorithm implemented in “The Visualization Toolkit” (VTK). During the 3D-reconstruction process of the surface models the
border of an anatomical structure on one cross-section is connected to the next with triangles.

*Three-dimensional measurements*

For the 3D analysis of the hip joint geometry a software program was developed called 3D Goniometer. It consists of an axis and a plane perpendicularly placed on one end of the axis. Point of view and sizing of the whole 3D scene can be changed by direct mouse interaction on the display window. In addition, the axis tool can be positioned independently from the anatomical bone structures. One can define an anatomical axis on the 3D bone structures interactively by positioning the axis tool along the presumed anatomical axis. After all necessary axes are determined and stored, at the result part of the GUI window the needed angles are printed out. For pathoanatomical analysis and accurate planning of surgical treatment it is essential to know the following angles: shaft-neck angle and femoral neck torsion (fig. 3), physis-shaft angle and physeal torsion (fig. 4), acetabular anteversion and inclination (fig. 5).

![Figure 3. Shaft-neck angle (left) and femoral neck torsion (right).](image)
These angles describe the geometry of the proximal femur, the degree of slippage and the orientation of the acetabulum. For the measurement of these angles it is necessary to determine the axis of the femoral shaft, the knee condyles, the femoral epiphysis, femoral neck, and the acetabulum (fig. 6).
Figure 6. Acetabular and femoral axis.

Measurement of range of motion (ROM) and simulation of osteotomies

The second part of our planning concept was developed to enable the surgeon to measure the range of motion of the hip joint pre- and postoperatively and to simulate different techniques of osteotomies of the proximal femur. The software allows the surgeon to move and rotate the selected 3D bone structure interactively and independently from all other anatomical structures along the 3 axis of the coordinate system as illustrated in figure 7 (left). The center of rotation of the hip joint is defined as the center of the femoral head. The range of motion is limited by an unphysiological contact (bone-bone or bone-cartilage (joint space)) between the femoral metaphysis and the acetabulum (fig. 7 -right).
In patients with SCFE the affected lower limb is regularly external rotated during the CT scan, caused by pain and the changed anatomy. After we had positioned the coordinate system at the center of rotation and before measuring the ROM, we performed an internal rotation up to a complete compensation of the external rotation (fig. 8).
When the preoperative analysis of the hip joint geometry and the measurement of the range of motion are performed, one can simulate different techniques of osteotomies of the proximal femur as subcapital, base-of-neck, intertrochanteric, or subtrochanteric techniques. The coordinate system enables to perform cuts through bony structures in any plane and at any angle as illustrated in figure 9.

**Figure 9.** Simulation of a three-dimensional intertrochanteric flexion, valgisation and internal rotation wedge osteotomy as described by Imhaeuser.

**Validation**

The presented three-dimensional preoperative planning concept was validated by two phantom studies. To validate the 3D Goniometer a wooden stick was used to simulate a femoral shaft. Smaller sticks penetrating the ends of this "shaft" simulated two condylar axes and three femoral neck axes. The angles between the axes were measured by conventional goniometers. The phantom was scanned (CT) in two different positions with the same scanning protocol. Postprocessing was performed in the same manner like described earlier. Six shaft-neck angles and twelve torsional measurements of the neck were performed. The average difference between the 3D digital model compared with the measurements on the real phantom was 0.02° for the shaft-neck angles and 0.06° for the torsion measurement. Analogous to that, the
validation of the second software tool was performed by using a wooden spheroid joint model which allows to rotate a small wooden stick at the end of the ball around three axis. The average difference between the 3D model and the joint model was 1.92° in 12 measurements.

**Discussion**

The major reason for the progress of imaging techniques is the improving computing strength, which provides an increasing ability for post-processing of radiographic images. One modern feature often available on recent CT and MRI consoles is to create 3D surface models from a series of cross-sectional images.

Angular measurements on bony structures are crucial for pathoanatomical analysis, diagnosis and therapeutically planning in cases of SCFE. So far, these angles are determined on plain radiographs [13, 14, 27]. This requires a correct positioning and an appropriate understanding of the projectional representation of anatomical structures. The analysis of plain radiographs is, even performed in a correct position of the patient, difficult to interpretive caused by the overlay of anatomical structures. Two main reasons complicate this in patients with SCFE. Currently, diagnosis and surgical preoperative planning is based on anterior-posterior and lateral plain x-rays. However, a correct positioning of these patients is regularly impossible. The affected lower limb is regularly external rotated and difficult to rest in a correct frog-leg position caused by pain and the changed anatomy. This and the complex three-dimensional deformity of the proximal femur itself characterized by the slippage, the changed orientation of the femoral neck [8, 17, 23, 26, 28], and the deformity of the femoral metaphysis [21] difficult the interpretation of these radiographs. 2DCT measurements provide angles without projected errors, whereas inaccuracies caused by the external rotation of the lower limb are still present. In contrast to that, the 3D Goniometer enables the user to analyse plain radiographs independently from the position of the patient and without projectional errors.

Goal of redirectional osteotomies of the proximal femur in patients with SCFE is to reconstruct the geometry of the hip joint and thereby to prevent degenerative joint disease and to improve the hip function. Therefore information about the geometry of both joint partners - the acetabulum and the femur - is required. The orientation of the acetabulum is described by the anteversion and the inclination. However, plain
radiographs only provide the acetabular inclination, whereas the anteversion is not measurable. In addition, the irregular surface of the acetabular rim complicates the accurate measurement of the inclination. Further postprocessing of two-dimensional CT data sets provides both angles whereas the accuracy of these angles is likewise reduced by the irregular rim of the acetabulum. The perpendicular plane at the end of the axis of the 3D Goniometer facilitates to define the orientation of the Acetabulum in both planes in an accurate and reproducible way.

In addition the 3D Goniometer is a useful tool to perform pathoanatomical investigations. The presence of a well centered femoral head is essential for a normal development of the acetabulum. In patients with SCFE the capital femoral epiphysis slips usually posteroinferiorly [8]. Thus, a normal acetabular development may be disturbed. Although a few articles described the acetabular anteversion based on 2D CT data sets there is [28], to our knowledge, no three-dimensional radiological analysis of the acetabular anteversion and inclination in patients with SCFE. Femur remodeling describes the process of reorientation of the proximal femur during the first two years after the slippage [30]. Some authors prefer to perform a late realignment osteotomy in cases of severe SCFE on the supposition that a remodeling of the femoral neck will improve the femoral orientation. A normal development of the acetabulum would support this procedure. In addition preventive fixation of the contralateral hip in cases of unilateral SCFE is discussed controversial. Former 2DCT studies reported that SCFE is associated with a reduced femoral anteversion [8, 28] and a varus deformity of the femur [17, 23, 26]. No article was found about a three-dimensional analysis of the geometry of the femur in both planes. A changed geometry of the unaffected proximal femur should be taken into account when considering about preventive fixation of the unaffected contralateral epiphysis.

Goals of redirectional osteotomies are to improve the hip function and to prevent a secondary coxarthrosis. One probable reason for the potential degenerative changes of the hip joint is an impingement between the antero-cranial acetabular rim and the femoral metaphysis. The slippage itself, the varisation and the reduced anteversion of the femoral neck and, the deformity of the femoral metaphysis as described by Murrey [21], may cause this impingement. Potential consequence of this impingement is an unphysiological bone-cartilage contact and a levering of the femoral head out of the acetabulum when the hip is flexed or abduced. Thus, all these anatomical changes
including the acetabular orientation should be taken into account when planning redirectional osteotomies.

Several authors recommend different techniques of reorientation osteotomies as subcapital, base of neck, intertrochanteric and subtrochanteric techniques [1, 5, 6, 13, 14, 15, 18, 22, 25, 27]. Main differences between these osteotomies are the degree of reconstruction and the rate of complications. In general one can say that the risk to develop a postoperative femoral head necrosis is lower for the intertrochanteric and subtrochanteric osteotomies in comparison with the subcapital osteotomies [2, 11, 14, 29]. Subcapital osteotomies however allow a more physiological reconstruction of the hip joint geometry.

The second part of the concept enables the surgeon to simulate and to compare all the recommended techniques of osteotomies of the proximal femur. One can evaluate the postoperative improvement of the range of motion and the degree of the reconstruction of the hip joint geometry. In addition one can apply the concept for further diseases of the hip joint. For instance it is useful for planning of osteotomies of the proximal femur in patients with aseptic femoral head necrosis.

Accurate three-dimensional measurements, additional anatomical information, the possibility to simulate different techniques of osteotomies and to evaluate the simulated postoperative result enables the surgeon, with regard to the clinical findings, to decide for the best surgical treatment.

References


