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SYMPOSIUM: FEMOROACETABULAR IMPINGEMENT: CURRENT STATUS OF DIAGNOSIS AND TREATMENT

Femoral Morphology Due to Impingement Influences the Range of Motion in Slipped Capital Femoral Epiphysis

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Abstract Femoroacetabular impingement due to metaphyseal prominence is associated with the slippage in patients with slipped capital femoral epiphysis (SCFE), but it is unclear whether the changes in femoral metaphysis morphology are associated with range of motion (ROM) changes or type of impingement. We asked whether the femoral head-neck junction morphology influences ROM analysis and type of impingement in addition to the slip angle and the acetabular version. We analyzed in 31 patients with SCFE the relationship between the proximal femoral morphology and limitation in ROM due to impingement based on simulated ROM of preoperative CT data. The ROM was analyzed in relation to degree of slippage, femoral metaphysis morphology, acetabular version, and pathomechanical terms of "impaction" and "inclusion." The ROM in the affected hips was comparable to that in the unaffected hips for mild slippage and decreased for slippage of more than 30°. The limitation correlated with changes in the metaphysic morphology and changed acetabular version. Decreased head-neck offset in hips with slip angles between 30° and 50° had restricted ROM to nearly the same degree as in severe SCFE. Therefore, in addition to the slip angle, the femoral metaphysis morphology should be used as criteria for reconstructive surgery.

Introduction

Slipped capital femoral epiphysis (SCFE) is characterized by displacement of the femoral metaphysis anteriorly and cranially with relative posterior and inferior positioning of the femoral head [1, 15]. Due to the proximal femoral deformity, femoroacetabular impingement between the anterocranial femoral metaphysis and the adjacent acetabulum may result [11], which may lead to osteoarthrosis of the hip [2, 3, 12, 16, 17, 21].

Rab [16] described two different types of femoroacetabular impingement based on a theoretical analysis of the proximal femoral geometry. "Impaction" type of impingement occurs when the proximal femoral metaphysis comes in contact with the acetabular rim, which limits the range of motion (ROM) of the hip, resulting in damage to the anterior part of the acetabular labrum. Levering of the femoral head out of the acetabulum would occur during

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Each author certifies that his or her institution has approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

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flexion and result in articular cartilage damage on the contralateral acetabulum. "Inclusion" type occurs when the proximal femoral metaphysis enters the acetabulum. The increase in radii of curvature from the metaphyseal bone can cause increased loading within the acetabulum, which can lead to articular cartilage damage.

The cartilage damage due to the proximal hip deformity postulated by Rab [16] based on his theoretical analysis has been validated to some extent by some clinical observations [5, 12]. Damage to the anterocranial acetabular cartilage and labrum was found on hip arthroscopy in four patients with acute to chronic hip pain with SCFE before in situ pinning [5]. Similarly, in 13 patients with SCFE, Leunig et al. [12] observed the association of a prominent or malaligned femoral metaphysis with acetabular cartilage and labral damage in cases with mild, moderate, and severe slippage. The femoral cartilage was intact in all of these patients. Similar to Rab [16], based on these findings, Leunig et al. [12] proposed a hypothesis for the etiology and pathogenesis of these findings in SCFE: in mild and moderate degrees of SCFE, the proximal femoral metaphysis is "included" into the acetabulum, resulting in a "jamming" effect, which can damage the acetabular cartilage. This is the cam type impingement [8]. In severe cases, an "impaction" occurs with development of pathologic loading at the acetabular labrum, resulting in a pincer type impingement. They concluded based on his findings this could be a trigger for development of osteoarthritis in patients with SCFE [12].

Despite these intraoperative observations, the long-term clinical outcome after mild to moderate SCFE treated with in situ pinning is generally good in terms of radiographic signs for osteoarthritic changes and good clinical outcome based on Iowa hip score [3]. However, we believe there is an inconsistency between outcome studies showing good long-term radiographic results and our understanding of the cartilage degeneration occurring mechanically in the hip with SCFE as described by intraoperative findings in patients with SCFE [5, 12]. In addition the role of acetabular version, which will additionally influence ROM and will affect the pattern of articular damage, was not accounted for in the theoretical analysis by Rab [16] and the clinical observations in patients with SCFE studies [5, 12]. Computer simulation of hip motion based on computed tomography (CT) bony models can confirm Rab's theoretical analysis of the effect of femoral head slippage and acetabular version on the hip ROM. Furthermore, it is possible to analyze how pathologic alterations in the transition of the convexity of the epiphysis into a concavity of the proximal metaphysis (using the criteria described by Jones et al. [9]) influence ROM Femoroacetabular impingement is a dynamic phenomenon. It is possible the good long-term clinical results in mild SCFE may be due to metaphyseal remodeling and patient adaptation to limitation in hip ROM. Furthermore, with an improved understanding of the cause of abnormal mechanics in SCFE, our surgical reconstruction techniques may be refined. For example, if the relative importance of the metaphyseal prominence versus the altered head-neck alignment is better understood, the relative importance of performing an osteoplasty versus osteotomy may be better defined.

We hypothesize proximal femoral head-neck junction morphology classified based transition of the convexity of the epiphysis into a concavity of the proximal metaphysis is just as important in determining the hip ROM in patients with SCFE as the slip angle. We also hypothesize that acetabular version influencing assessment of ROM in patients with SCFE. Furthermore, we hypothesize the type of mechanism for impingement as described by Rab [16] is influenced in SCFE by the amount of slippage and the type of femoral head-neck junction morphology as classified by Jones et al. [9] and not by acetabular version.

Materials and Methods

We retrospectively analyzed 31 selected patients with SCFE who had radiographs and a CT scan before treatment. There were no unstable SCFEs in this group. We analyzed data from 14 female and nine male patients with an average age of 13.7 years (10.4–16.8 years). There were 15 unilateral and eight bilateral cases. The right hip was affected in 11 cases, the left in 20 cases. The CT acquisition was performed at the time of diagnosis before obtaining surgical treatment. As typical of chronic stable SCFE, the onset of symptoms to diagnosis varied. Additionally, the time to CT scanning varied and was not controlled for in this retrospective study. Fifteen contralateral hips were used as a normal comparison group. Institutional review board approval was obtained for this study.

Radiographic analysis included assessment of slip angle and classification of the transition of the convexity of the epiphysis into a concavity of the proximal metaphysis to assess femoral metaphysis morphology. The degree of slippage was assessed based on the method described by Southwick [19]. For the determination of inferior angle of slippage (α), a standard anteroposterior radiograph was used. For the posterior slippage (β), a frog leg radiograph was used. The degree of slippage was calculated as the difference between the epiphyseal plate angles of the affected and the unaffected sides. In bilateral cases, instead of the unaffected side epiphyseal angle, the means of the epiphyseal plate angles of the unaffected hips ($n = 15$) were used ($\alpha = 142.5°$, $\beta = 14.3°$). The mean inferior

Table 1. Amount of slippage according to Southwick [20] (mild, moderate, severe) with consideration of femoral metaphysis morphology according to Jones et al. [9] (Type 1 − 3)

Severity of slippage/ femoral morphology type	Number of hips	Inferior slippage	Posterior slippage
Mild 1	9	14.5° ± 9.2°	10.5° ± 2.1°
Mild 2	3	25.0° ± 1.3°	11.3° ± 4.0°
Mild 3	0		
Moderate 1 + 2	4	37.9° ± 5.2°	14.9° ± 5.0°
Moderate 3	3	47.7° ± 2.8°	28.1° ± 3.6°
Severe 1	0		
Severe 2	8	63.5° ± 9.4°	30.1° ± 9.8°
Severe 3	4	55.5° ± 5.7°	21.0° ± 8.5°

Values are expressed as mean ± standard deviation.

slippage angle in the affected hips was 39.4° ± 21.6° (mean ± standard deviation), and the mean posterior slippage angle was 19.4° ± 10.9°. The amount of slippage was classified as mild (n = 12) for less than 30°, moderate (n = 7) for 30° to 50°, and severe (n = 12) for more than 50° (Table 1).

The proximal femoral morphology on the frog lateral views was classified using the criteria defined by Jones et al. [9] (Fig. 1). Type 1 is defined by a normal geometry of the ventral femoral head-neck junction. The convexity of the epiphysis transitions into a concavity of the proximal metaphysis such that an anterocranial prominence as described by Murray [14] cannot be observed [13]. For cases of Type 2, the ventral margin of the epiphysis is aligned with the ventral margin of the metaphysis and therefore in the same level. In cases of a convex profile, where the ventral margin of the femoral head is located distal to the femoral metaphysis, a Type 3 is defined. Additionally, a bony prominence of the femoral metaphysis can be observed. Jones et al. [9] considered Type 1 and 2 to be a remodeled metaphysis in cases of SCFE, while Type 3 was the result of incomplete remodeling.

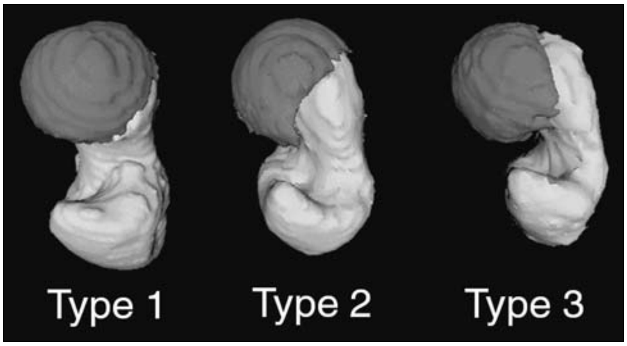

Fig. 1 Diagrams illustrate Type 1 to 3 proximal femoral remodeling classified according to the criteria of Jones et al. [9]. Type 3: The proximal femoral epiphysis is positioned dorsal in relation to the metaphysis. A ventral located bony prominence in the region of the proximal femoral metaphysis can be observed. Type 2: The femoral epiphysis and metaphysis are on the same level in ventral direction. Type 1: The normal anatomic morphology of the ventral transition between the femoral epiphysis and metaphysis is shown.

CT scans of the hips were initially obtained to look at the association of the femoral retroversion with SCFE [6]. This data set was reanalyzed retrospectively for this study. The patients were examined supine with 2- to 5-mm contiguous, axial slices with in-plane resolution of 0.5 × 0.5 mm through the hip and the femoral condyles. The CT data were postprocessed in terms of segmentation with a commonly used intensity thresholding technique to delineate the structures of interest semiautomatically to ensure separation of pelvis and femur and to determine the border between the femoral head and neck. Three-dimensional models of the segmented files of the femoral condyles, proximal femur, femoral epiphysis, femoral head, and acetabulum were reconstructed using marching cubes [16], an algorithm implemented in the Visualization Toolkit (VTK) (Kitware Inc, Clifton Park, NY) and a triangle reduction algorithm [17], which also uses the VTK libraries.

To determine the acetabular version from the CT scans, a software program described by Kordelle et al. [11] was used, which enables assessment without projectional and pelvis-tilting errors. Therefore, an acetabular plane was positioned parallel to the three bony eminences at the ventral, dorsal, and superior parts of the acetabular margin and the version was calculated (Fig. 2).

The ROM data were obtained from CT scans using custom-designed software that determines the hip ROM by detecting bone to bone contact [17]. This simulation does not take into account the soft tissue constraints, therefore providing a theoretical maximum ROM and not actual ROM; hence, we did not correlate the results to clinically measured ROM. The program allows separation and manipulation of the single three-dimensional structures independently. The ROM was assessed by placing the

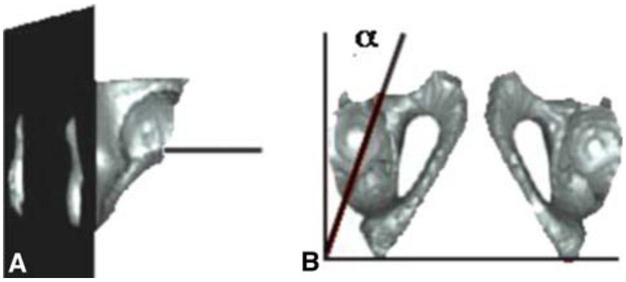

Fig. 2A–B Diagrams illustrate the assessment of the acetabular version based on a three- dimensional model of the acetabulum: (**A**) dorsolateral view of the acetabulum and (**B**) position of the acetabular version (α).

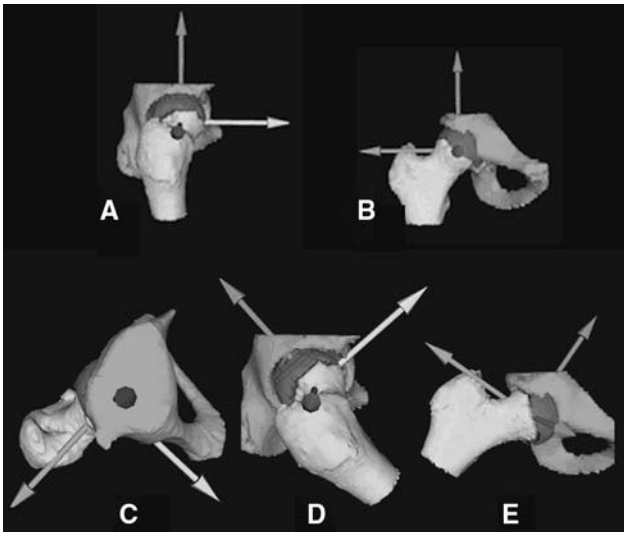

Fig. 3A–E Using a three-dimensional model of the proximal femur, ROM is assessed in relation to neutral position: (**A**) neutral position in lateral view, (**B**) neutral position in frontal view, (**C**) rotation, (**D**) flexion, and (**E**) abduction.

center of the coordinate system in the center of the femoral head. The three-dimensional model of the proximal femur was then rotated through the center of the femoral head around the axis perpendicular to the sagittal, coronal, and axial planes to obtain flexion, abduction, and internal rotation measurements (Fig. 3).

In 12 cases the affected limbs were in external rotation at rest on the CT scan. During ROM analysis, all femora were rotated to make the tangent line to the dorsal contours of the distal femoral condyle parallel to the floor (neutral zero method) [4, 7]. This was necessary to define a common neutral starting point for the ROM analysis. Both the affected (n = 31) and unaffected (n = 15) hips were analyzed independently.

The types of impingement limiting the ROM on simulation were classified using the criteria defined by Rab [16]. "Inclusion" occurred when there was penetration of the femoral metaphysis into the acetabular opening, before limitation of the ROM by contact at the acetabular rim. At this point, nonphysiologic bone/cartilage contact occurs between the acetabular cartilage and the included metaphyseal bone. An "impaction" type impingement occurred when there was direct contact between the femoral metaphysis and the acetabular rim, which blocks further movement.

The accuracy of ROM measurements was validated using a wood model phantom. The model consists of four opposing blocks of wood of different size to distinguish each one on the CT scan, obtained with 1-mm slice thickness and same in-plane resolution as the patient scans. In the center of the model, a cylinder contains ⅓ of an overlaying bowl to simulate the ball and socket joint. A stick positioned perpendicular to the base of the cylinder is affixed on the bowl for simulation of the movement. Two opposing blocks of wood act as reference for measurement of the flexion/extension or abduction/adduction. The horizontal movement of the stick between two blocks is defined as rotation (Fig. 4).

Using the wood model phantom, abduction, adduction, flexion, extension, internal rotation, and external rotation were simulated and the angles measured manually and on CT three times. The manual and CT measurements were compared using Student's t test. The two measures were similar, except for flexion which differed (p = 0.008) by 3.3° between the manual and CT measurements.

All simulated measurements of ROM and acetabular version were performed by three independent observers (JK, CPK, TCM) and the mean value of these observations was calculated. Kolmogorov-Smirnov test showed normal distribution for all measurements for ROM. Differences in ROM between the amount of slippage and classification of the femoral head-neck offset were determined by Student's t test, influence of the Jones classification on the femoral head-neck offset to the ROM analysis by Spearman rank correlation. To correlate the influence of acetabular version on ROM, we used Pearson correlation coefficient. The assessment of femur metaphysis morphology and impingement was performed by consensus pattern. For the analysis, we used SPSS® 12.0 (SPSS Inc, Chicago, IL).

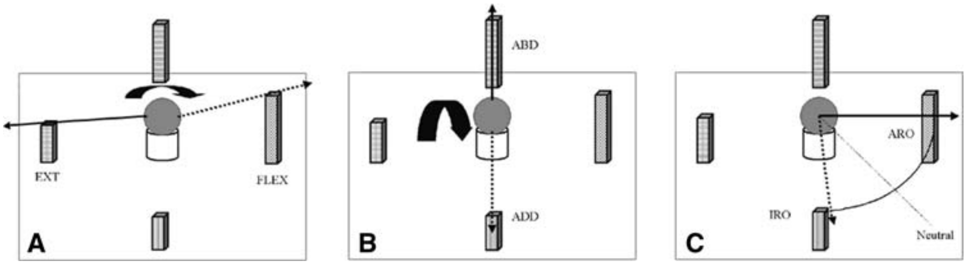

Fig. 4A–C Diagrams illustrate the model for validation of the ROM measurement program: (**A**) simulation of flexion, (**B**) simulation of abduction, and (**C**) simulation of rotation. EXT = extension; FLEX = flexion; ADD = adduction; ABD = abduction; IRO = internal rotation; ARO = external rotation.

Table 2. Range of motion in relation to acetabular version, amount of slippage according to Southwick [20] (mild, moderate, severe), and femoral metaphysis morphology according to Jones et al. [9] (Type 1–3)

Severity of slippage/ femoral morphology type	Acetabular version	Flexion	Abduction	Internal rotation
Mild 1	13.9° ± 5.9°	97.8° ± 25.4°	65.9° ± 8.7°	96.2° ± 20.6°
Mild 2	11.2° ± 4.9°	61.8° ± 33.8°	57.4° ± 12.8°	74.9° ± 27.1°
Mild 3				
Total mild	13.1° ± 5.9°	88.8 ° ± 20.5°	64.0 ° ± 10.0°	90.9 ° ± 23.1°
Moderate 1 + 2	13.8° ± 0.9°	25.7° ± 17.8°	24.2° ± 20.1°	36.0° ± 21.8°
Moderate 3	11.1° ± 0.8°	2.0° ± 24.5°	9.8° ± 5.1°	3.0° ± 33.3°
Total moderate	12.4° ± 1.5°	14.2° ± 24.1°	18.0° ± 16.4°	21.8° ± 30.3°
Severe 1				
Severe 2	11.1° ± 5.3°	3.9° ± 15.2°	4.9° ± 24.6°	7.4° ± 26.3°
Severe 3	12.8° ± 4.3°	5.4° ± 7.4°	6.3° ± 10.3°	10.1° ± 17.7°
Total severe	11.6° ± 4.8°	4.4° ± 12.4°	5.5° ± 19.9°	8.4° ± 22.6°
Unaffected side	11.4° ± 4.7°	99.1° ± 12.1°	69.7° ± 15.3°	96.3° ± 26.2°

Values are expressed as mean ± standard deviation.

Results

Femoral metaphysis morphology and amount of slippage influenced amount of ROM (Table 2). For mild slippage, the ROM is comparable to the unaffected side: 88.8° ± 20.5° versus 99.1° ± 23.1° for the flexion ($p = 0.77$), 64.0° ± 10.0° versus 69.7° ± 15.3° for abduction ($p = 0.94$), and 90.9° ± 23.1° versus 96.3° ± 26.2° for internal rotation ($p = 0.58$). But, even with a mild slip angle, if there was a decreased head-neck offset (Jones Type 2), there was a trend toward decreased ROM, most of all for flexion: 61.8° ± 19.5° for flexion ($p = 0.23$), 57.4° ± 7.3° for abduction ($p = 0.48$), and 74.9° ± 15.6° for internal rotation ($p = 0.24$). For moderate slippage, there was a decrease in flexion ($p = 0.002$), abduction ($p = 0.0032$), and internal rotation ($p = 0.004$) compared to the unaffected side, which was made worse with progressive loss of the femoral head-neck offset. For severe slippage, regardless of the proximal femoral anatomy, there was near-complete loss of normal motion. Femoral metaphysis morphology correlated with ROM (–0.837 for flexion, −0.852 for abduction, and −0.825 for internal rotation) (Fig. 5).

We observed no differences in acetabular version between the affected and unaffected side and no differences in relation to amount of slippage (Table 2). Acetabular version weakly correlated with ROM, with decreased acetabular version associated with loss of ROM: −0.334 for flexion, −0.314 for abduction, and −0.317 for internal rotation.

Impingement mechanism correlated with femoral metaphysis morphology and amount of slippage (Table 3). When the mechanisms of impingement were analyzed at the time of ROM analysis, for mild slippage, there was only inclusion type impingement ($n = 12$). For severe slippage, five of eight Jones Type 2 had impaction

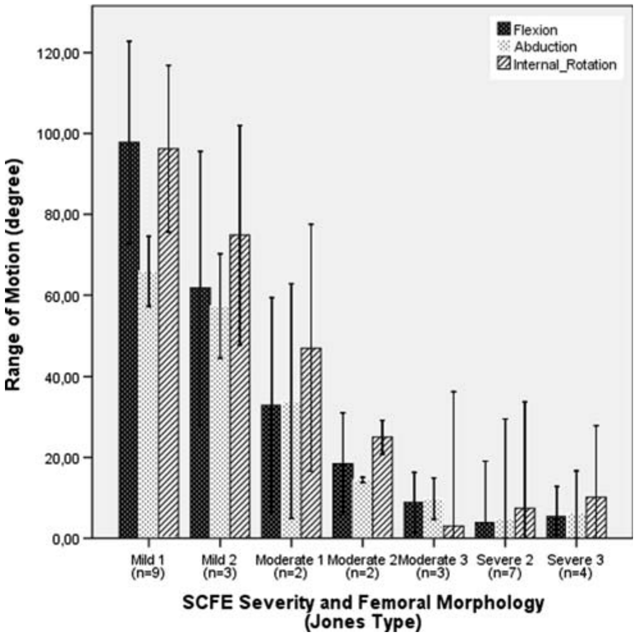

Fig. 5 The influence of femoral metaphysis morphology (Jones type) in addition to the amount of slippage for restriction in ROM is shown in the histogram. For mild slippage, a decrease for flexion is shown between Types 1 and 2 but no changes for internal rotation and abduction. For moderate slippage, ROM decreased as femoral metaphysis deformity increased (emphasized by the red line). For severe slippage, there was near-complete loss of normal ROM regardless of the proximal femoral anatomy. The correlation coefficients (Spearman) are −0.837 for flexion, −0.852 for abduction, and −0.825 for internal rotation.

Table 3. Comparison of impaction and inclusion for severity of slippage according to Southwick [20] (mild, moderate, severe) with consideration of femoral metaphysis morphology according to Jones et al. [9] (Type 1–3)

Severity of slippage/ femoral morphology type	Number of hips	Inclusion	Impaction
Mild 1	9	9	0
Mild 2	3	3	0
Mild 3	0		
Moderate 1	2	2	0
Moderate 2	2	1	1
Moderate 3	3	0	3
Severe 1	0		
Severe 2	8	3	5
Severe 3	4	0	4

type impingement, while the more severe Jones Type 3 had all impaction type impingement (n = 4). For moderate slippage, the type of impingement trended toward the impaction type in hips with decreased head-neck junction. There were no differences in acetabular version for inclusion (12.2° ± 2.9°) or impaction type (12.3° ± 3.2°).

Discussion

Femoroacetabular impingement due to metaphyseal prominence is associated with slippage in patients with slipped capital femoral epiphysis (SCFE), but it is unclear whether the changes in femoral metaphysis morphology are associated with ROM changes or type of impingement. We questioned whether the femoral head-neck junction morphology influences ROM analysis and type of impingement in addition to the slip angle and the acetabular version.

Our study has several limitations. First is the relatively small number of patients in the study. In moderate SCFE, we observed a nonsignificant trend toward decreased ROM in Jones Type 2 and 3 versus Type 1, which may be due to the small sample size. Despite the small number of patients, we were able to find correlations showing influence of different Jones type to ROM. However, slip severity and femoral neck morphologic types are covariates for which we could not control with the limited numbers. Second, additional proximal femoral anatomy variables such as femoral retroversion and femoral neck-shaft angle that would influence the hip ROM, which were addressed in other studies [9, 10, 17–20], were not addressed in ours. Our conclusions are based on the assumption that femoral morphology is not strongly associated with either femoral retroversion or neck-shaft angle. This would have to be addressed in future studies. Third, we did not account for either soft tissue or cartilage due to current technical limitations. In the model of femoroacetabular impingement, these do not need to be taken into account since the acetabular labrum would only lead to a slight difference in ROM. By assessing the bony anatomy, we were considering only one of the factors leading to joint degeneration in SCFE. Soft tissue restraints and activity level, as well as bony anatomy, will lead to joint degeneration. Fourth, clinical followup in patients with mild to moderate slippage suggests good functional outcomes in contrast to the results found in our assessment of pretreatment hips. Therefore, followup data are needed for further investigation of the role of remodeling and impingement. However, the femoral metaphysis morphology was classified based on the criteria of Jones et al. [9], which is used to describe removal of the SCFE deformity in terms of remodeling. Therefore, if femoral head-neck junction remodeling should occur, our results are still applicable in terms of understanding the improvement in ROM. Finally, using CT data for analysis, it is not feasible to analyze the articular cartilage as they might correlate with our findings. However, based on the findings of Leunig et al. [12] and Futami et al. [5], the pathomechanism of femoroacetabular impingement leads to corresponding lesions of the acetabular cartilage and the labrum.

The assessment of ROM based on CT simulation in correlation to slippage and femoral metaphysis morphology showed in mild SCFE no bony restrictions within clinically normal ROM, which is consistent with good long-term results after in situ pinning [2, 3, 22]. As expected, in cases of severe SCFE, there was a decrease in hip ROM up to a complete loss. The loss of internal rotation implies all severe SCFE will walk with the limb externally rotated. Additionally, in order for the hip to flex, the hips must externally rotate in severe SCFE. However, even for moderate SCFE, a marked reduction in ROM could be observed, which is not compatible with normal activities of daily living. Given the importance of femoroacetabular impingement as a cause of hip pain and articular cartilage damage and the importance of the metaphyseal prominence in determining ROM, it appears that the proximal femoral morphology should be addressed at time of surgical reconstruction. This would be one possible explanation for the higher incidence of osteoarthritic changes compared to the normal population in long-term followup studies of pinning in situ for mild and moderate slippage. But, because of the additional restriction of ROM due to soft tissue conditions, the actual rate of impingement occurring in the patient population in daily living activity differs from findings in our population and therefore a prediction cannot be made based on these data. With Jones Type 3, there is impingement even in near extension and neutral rotation, implying, in moderate SCFE, if the proximal femur can remodel, the external rotation gait may improve. Even in extension in moderate and severe SCFE, the distal femur would rest in external rotation. When the distal femur is brought back to neutral, the marked decrease in hip flexion and internal rotation can be demonstrated. This would explain the apparent discrepancy between clinical hip ROM measurements in the supine position and CT simulated ROM. Therefore, with the leg starting in external rotation, the clinical ROM in these patients will be better compared to our simulated measurements.

Based on a theoretical geometric analysis, Rab [16] showed there is an obligatory external rotation for moderate to severe SCFE during hip flexion. We have verified this finding using actual patient CT data and simulated ROM. We have also found "impaction" and/or "inclusion" of the proximal femoral metaphysis as the cause of hip ROM limitation. However, because of the cross-sectional nature of our data, we are not able to look at the effects of femoral neck remodeling from "impaction" to "inclusion" types.

For acetabular version, we found no differences between the affected and unaffected sides and no differences for degree of slippage, which confirms results described by Kordelle et al. [11] on development of the acetabulum in patients with SCFE. Also, no differences for the impingement type could be assessed, emphasizing the importance of femoral metaphysis changes in SCFE. However, we found a weak correlation between decreased acetabular version and loss of ROM, indicating the importance of acetabular version in addition to femoral metaphysis morphology in ROM of the hip.

Based on our data, hips with moderate SCFE and with decreased head-neck offset had restricted ROM to nearly the same degree as hips with severe SCFE. Therefore, in addition to the slip angle, the femoral head-neck junction morphology should be used as a criterion for reconstructive surgery. Hence, these data illustrate the importance of addressing the abnormal head-neck junction morphology during surgery. For example, in mild SCFE, if a large metaphyseal prominence is present, a simpler procedure of femoral head-neck junction osteoplasty may be sufficient. Conversely, in moderate to severe SCFE, intertrochanteric osteotomy alone can improve ROM but is unlikely sufficient to relieve the impingement.

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