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Limited Hip Flexion and Internal Rotation Resulting From Early Hip Impingement Conflict on Anterior Metaphysis of Patients With Untreated Severe SCFE Using 3D Modelling

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Introduction: Slipped capital femoral epiphysis (SCFE) is the most common hip disorder in adolescent patients that can result in complex 3 dimensional (3D)-deformity and hip preservation surgery (eg, in situ pinning or proximal femoral osteotomy) is often performed. But there is little information about location of impingement. Purpose/Questions: The purpose of this study was to evaluate (1) impingement-free hip flexion and internal rotation (IR), (2) frequency of impingement in early flexion (30 to 60 degrees), and (3) location of acetabular and femoral impingement in IR in 90 degrees of flexion (IRF-90 degrees) and in maximal flexion for patients with untreated severe SCFE using preoperative 3D-computed tomography (CT) for impingement simulation.

Methods: A retrospective study involving 3D-CT scans of 18 patients (21 hips) with untreated severe SCFE (slip angle > 60 degrees) was performed. Preoperative CT scans were used for bone segmentation of preoperative patient-specific 3D models. Three patients (15%) had bilateral SCFE. Mean age was 13 ± 2 (10 to 16) years and 67% were male patients (86% unstable slip, 81% chronic slip). The contralateral hips of 15 patients with unilateral SCFE were evaluated (control group). Validated software was used for 3D impingement simulation (equidistant method).

Results: (1) Impingement-free flexion (46 ± 32 degrees) and IRF-90 degrees (−17 ± 18 degrees) were significantly ($P < 0.001$) decreased in untreated severe SCFE patients compared with contralateral side (122 ± 9 and 36 ± 11 degrees). (2) Frequency of impingement was significantly ($P < 0.001$) higher in 30 and 60 degrees flexion (48% and 71%) of patients with severe SCFE compared with control group (0%). (3) Acetabular impingement conflict was located anterior-superior (SCFE patients), mostly 12 o'clock (50%) in IRF-90 degrees (70% on 2 o'clock for maximal flexion). Femoral impingement was located on anterior-superior to anterior-inferior femoral metaphysis (between 2 and 6 o'clock, 40% on 3 o'clock and 40% on 5 o'clock) in IRF-90 degrees and on anterior metaphysis (40% on 3 o'clock) in maximal flexion and frequency was significantly ($P < 0.001$) different compared with control group.

Conclusion: Severe SCFE patients have limited hip flexion and IR due to early hip impingement using patient-specific preoperative 3D models. Because of the large variety of hip motion, individual evaluation is recommended to plan the osseous correction for severe SCFE patients.

Level of Evidence: Level III

Key Words: Hip, SCFE, slipped capital femoral epiphysis, femoroacetabular impingement, hip preservation surgery, in situ pinning

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Slipped capital femoral epiphysis (SCFE) is the most common hip disorder affecting adolescents. Patients are usually affected in adolescence. Recently, anatomic factors such as the epiphyseal tubercle and epiphyseal cupping were described.[1,2] In situ pinning allows for stabilization but often left the patients with femoral deformity leading to femoroacetabular impingement (FAI).[3,4] SCFE has been investigated since decades but only little information is known about biomechanics[5] and the exact location of hip impingement conflict is unclear.

One biomechanical study of 1999 reported that significant alterations in patient motion were needed to compensate for the SCFE deformity.[6] Although mild slips are generally well tolerated by patients, it was calculated that at least 10 degrees of excess external rotation (ER) were necessary to avoid metaphyseal impingement in a mild slip.[6] The amount of ER increased substantially with moderate and severe slips to 30 and 40 degrees.[6] Another study used computed tomography (CT) scans of 31 SCFE patients to simulate hip motion in patients with history of mild to severe SCFE.[7] They reported inclusion impingement for patients with mild SCFE, but as the severity increased, the impingement conflict switched to that of impaction on the acetabular rim.[7] They also found that the degree of range of motion (ROM) restriction was proportional to the severity of the SCFE.[7]

In situ pinning is the conventional treatment for a stable SCFE.[3] However, with a severe stable SCFE the residual deformity may lead to FAI and articular cartilage damage.[8] Although residual SCFE deformity may partially remodel after in situ pinning,[9] the remodeling process can lead to FAI, an abnormal early contact between the proximal femur and the anterior acetabular rim.[6] FAI secondary to SCFE has been reported to lead to articular cartilage damage,[10–13] which is related to the development of hip osteoarthritis.[14] To better understand the impingement conflict in SCFE patients, patient-specific 3 dimensional (3D) models were generated using 3D-CT.

Purpose The purpose of this study was to evaluate 3D impingement simulation for untreated severe SCFE patients.

The aims of this study was to evaluate (1) hip flexion and internal rotation (IR), (2) frequency of impingement in early flexion, and (3)location of acetabular and femoral impingement in IR in 90 degrees of flexion (IRF-90 degrees) and in maximal flexion for patients with untreated severe SCFE using preoperative 3D-CT for impingement simulation.

METHODS

A retrospective IRB-approved study involving 3D-CT scans of 21 hips of 18 patients with severe SCFE (slip angle > 60 degrees) was performed. Preoperative CT scans performed of patients with SCFE at the institution of the senior author between 1998 and 2016 were evaluated. Of patients with CT scans during this time period, we excluded patients with mild and moderate SCFE, postoperative or insufficient CT scans. Preoperative 3D models of 21 hips with severe SCFE were reconstructed to simulate hip ROM and location of hip impingement. Three patients (15%) had bilateral SCFE (Table 1). The contralateral hips of the 15 patients with unilateral SCFE were used as a control group.

Patient Selection

All 123 patients with bilateral pelvic CT scans during this time period were screened for the inclusion criteria: age 10 to 30 years and a diagnosis of SCFE that was untreated at the time of imaging. One hundred five patients were excluded due to the following reasons: mild (slip angle < 30 degrees) and moderate SCFE (slip angle 30 to 60 degrees), postoperative CT scans (eg, after previous femoral osteotomy or in situ pinning) or insufficient CT scans (eg, CT of unilateral hip joint or missing femoral condyles). No postoperative CT scan was included in this study. The remaining 21 hips (18 patients) were untreated severe SCFE patients with preoperative pelvic CT scan that included the femoral condyles.

Patient Characteristics

Mean age of the 18 patients was 13 ± 2 (10 to 16) years and almost half of the patients were male patients (Table 1). Most of the patients had a stable slip according to the Loder classification,[15] and most of the patients had a chronic slip (Table 1). Mean body mass index was 27 ± 5 kg/m^2, and the body mass index percentile was > 90% of the SCFE patients(Table 1). Surgical treatment

TABLE 1. Demographic Information of the Patient Series is Shown

Parameter	Value
Total hips (patients)	36 (18)
Total hips with severe SCFE (patients)	21 (18)
Total hips of asymptomatic controls (patients)	15 (15)
Age (y)	13 ± 2 (10-16)
Sex (% male of all hips)	48
Side (% left of all hips)	57
Height (cm)	166 ± 9 (152-179)
Weight (kg)	80 ± 12 (53-97)
BMI (kg/m^2)	27 ± 5 (22-36)
BMI percentile	93
Unstable hips according to Loder classification (% unstable of all hips)[18]	14
Severity based on slip Angle (% of all hips)	
Mild <30 degrees	0
Moderate 30-60 degrees	0
Severe > 60 degrees	100
Classification based on the duration of symptoms (% of all hips),[12]	
Acute	0
Acute on chronic	19
Chronic	81

Continuous values are expressed as mean ± SD and range in parenthesis.
BMI indicates body mass index; SCFE, slipped capital femoral epiphysis.

TABLE 2. Surgical Treatment of the Patient Series is Shown

Parameter	Value, n (%)
Total hips with severe SCFE	21
Surgery performed after CT	20 (95)
Flexion intertrochanteric osteotomy (n, % of all hips	7 (33)
Surgical hip dislocation and open offset correction (cam resection)	7 (33)
Relative femoral neck lengthening (distalisation of the greater trochanter)	4 (19)
In situ fixation	10 (48)
Modified Dunn procedure	4 (19)

One hip was not operated and 1 hip was operated twice.
None of the asymptomatic hips underwent prophylactic pinning.
CT indicates computed tomography; SCFE, slipped capital femoral epiphysis.

of the SCFE patients was performed in most of the hips (20 hips, 95%, Table 2). In situ fixation, flexion intertrochanteric osteotomy and also the modified Dunn procedure[16–18] was performed. The control group of 15 hips had a mean age of 13 ± 2 (10 to 16) years and 40% were male patient.

Imaging

All patients underwent standardized AP and lateral or frog-leg radiographs and CT scans of the pelvis and the distal femoral condyles[19] according to a previously described protocol.[20] We then generated a 3D bone model of the pelvis and the femur (Fig. 1) using the Amira Visualization Toolkit (Visage Imaging Inc, Carlsbad, CA). The acetabular reference coordinate system was the anterior pelvic plane, defined by both antero-superior iliac spines and the pubic tubercles.[21] To minimize radiation exposure, the anterior-superior iliac spines were not always covered in the CT. The anterior pelvic plane was therefore reconstructed using a plane formed by the inferior iliac spines and the pubic tubercles and a tilt angle of 20 degrees.[22] The femoral reference coordinate system was defined by the center of the femoral head, the knee center, and both femoral condyles.[23] Using this patient-specific 3D models derived from the CT scans, we compared ROM and individual impingement location.

3D Impingement Simulation

CT-based 3D models of 21 hips were evaluated using a validated 3D bony collision detection software to quantify the hip ROM and the acetabular and femoral location of impingement.[19,21] Bone-to-bone contact between the proximal femur and the acetabulum was evaluated. Each individual hip was virtually simulated with the help of previously described and validated software.[21] This software uses automatic rim detection, a best-fitting sphere algorithm for identification of femoral head center, and the equidistant method for motion analysis.[19] The equidistant method was specifically designed for virtual FAI analysis.[19] On the basis of a cadaveric investigation including cartilage, labrum, and joint capsule, an impingement collision can be detected with a mean accuracy of 2.6 ± 2.5 degrees.[19] Using this computerized analysis, we calculated the impingement-free flexion and IRF-90 degrees. In a validation study of this software, intra- and interobserver measurements for flexion and IRF-90 degrees were excellent (> 0.9), and good agreement[24] could be found for the interobserver interobserver correlation coefficien.[21] Furthermore, we evaluated a motion pattern, which correspond to the widely used anterior impingement test[25] (90 degrees flexion and IR).[26,27] Frequency of impingement and simulation of impingement-free ROM was calculated between 30 and 90 degrees of flexion. Impingement-free ROM was calculated to avoid bone-to-bone contact.

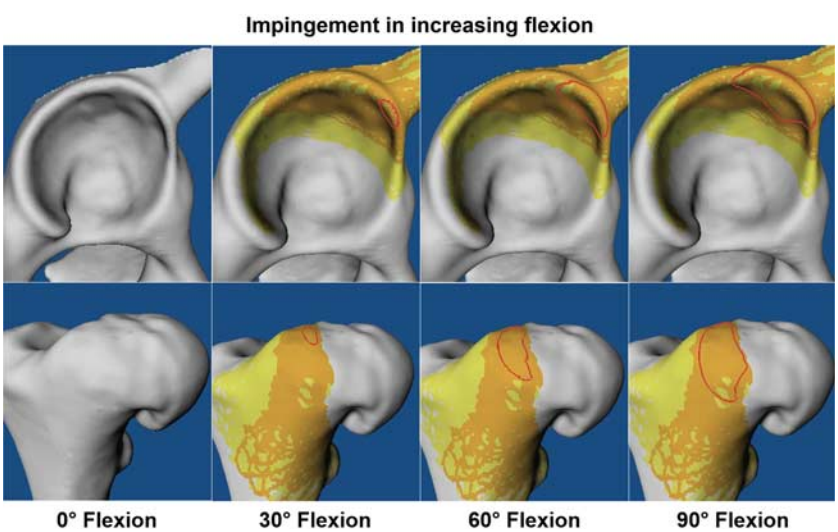

FIGURE 1. The 3D model of the acetabulum (above) and the proximal femur (below) of a patient with unilateral severe slipped capital femoral epiphysis is shown. Increasing impingement zones (red zone) are shown with increasing flexion (without adduction). Yellow and orange zone indicate theoretical further bony impingement in adduction, similar to the Flexion-adduction and internal rotation test.

TABLE 3. Range of Motion for Severe SCFE Patients and Asymptomatic Controls are Shown

Parameter	SCFE Patients	Asymptomatic Control	*P*
Total hips (patients)	21 (18)	15 (15)	
Flexion (deg)	46 ± 32 (0-113)	122 ± 9 (107-138)	< 0.001
Internal rotation in 0 degree of flexion (deg)	50 ± 27 (0-100)	120 ± 23 (85-155)	< 0.001
Internal rotation in 30 degrees of flexion (deg)	13 ± 33 (−35 to 80)	98 ± 16 (75-126)	< 0.001
Internal rotation in 60 degrees of flexion (deg)	−9 ± 23 (−50 to 29)	64 ± 18 (37-100)	< 0.001
Internal rotation in 90 degrees of flexion (deg)	−17 ± 18 (−60 to 10)	36 ± 11 (21–55)	< 0.001

Continuous values are expressed as mean ± SD and range in parenthesis.
SCFE indicates slipped capital femoral epiphysis.

The impingement zones for the anterior impingement test without adduction (Fig. 1 red zone) were calculated for femoral and acetabular location separately. The anterior impingement test with adduction (Fig. 1 orange and yellow zone) was simulated, similar to the Flexion-adduction and internal rotation (FADIR) test. The distribution of the impingement zones was calculated using a clock system[22,28] with 3 o'clock representing anterior. Three o'clock was consistently defined anteriorly for both right and left hips. In addition, the location of impingement was further specified as extra- or intra-articular. Intra-articular locations comprised the acetabular rim and the lunate surface on the acetabular side and the femoral head and neck on the femoral side.

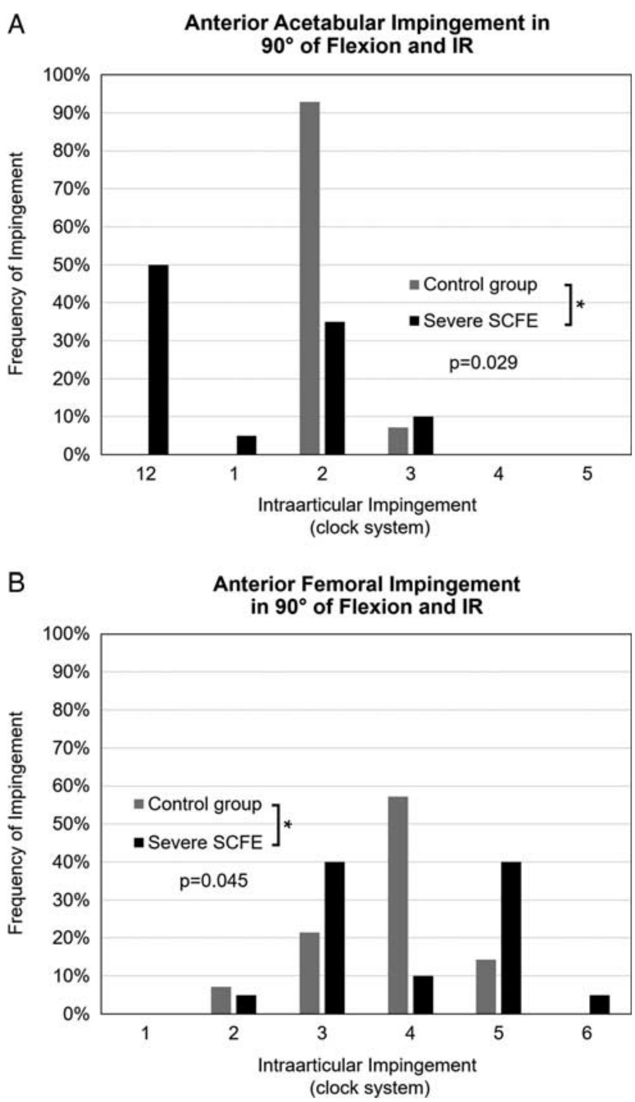

FIGURE 2. A and B, Location of acetabular (A) and femoral (B) impingement in internal rotation in 90 degrees of flexion is summarized below for 21 hips of severe SCFE patients. IR indicates internal rotation, SCFE, slipped capital femoral epiphysis.

The types of impingement limiting the ROM on simulation were analyzed using the criteria defined by Rab.[6] The so-called "Inclusion" type occurred in 2 hips (10%) when there was penetration of the femoral metaphysis into the acetabular opening. An "impaction" type impingement occurred most often (90%) when there was direct bone-to-bone contact between the femoral metaphysis and the acetabular rim, which blocks further movement (Video 1, supplementary material, Supplemental Digital Content 1, http://links.lww.com/BPO/A536).

Statistical Analysis

Normal distribution was tested using the Kolmogorov-Smirnov test. Because the data were not normally distributed, we only used nonparametric tests. To compare demographic and radiographic data, ROM, or location of impingement, we used the Mann-Whitney U test. To compare binominal demographic data and the prevalence of impingement we used the Fisher exact test.

RESULTS

(1) Impingement-free flexion (46 ± 32 degrees) was significantly ($P < 0.001$) decreased in patients with severe SCFE compared with the contralateral side (122 ± 9 degrees, Table 3). IRF-90 degrees (−17 ± 18 degrees) was significantly ($P < 0.001$) decreased in patients with severe SCFE compared with the contralateral side (36 ± 11degrees, Table 3). IR in 0 degree, in 30 and 60 degrees of flexion were also significantly ($P < 0.001$) decreased in patients with severe SCFE compared with the contralateral side.
(2) Frequency of impingement was significantly higher in 30 and 60 degrees flexion (48% and 71%) of patients

TABLE 4. Frequency of Impingement Conflict in Different Degrees of Flexion for Severe SCFE Patients and Asymptomatic Controls are Shown

Parameter	Severe SCFE Patients	Asymptomatic Control	*P*
Total hips (patients)	21 (18)	15 (15)	
0 degree of flexion, no rotation (hips, %)	0	0	—
30 degrees of flexion, no rotation (hips, %)	10 (48)	0	< 0.001
60 degrees of flexion, no rotation (hips, %)	15 (71)	0	< 0.001
90 degrees of flexion, no rotation (hips. %)	19 (90)	0	< 0.001
120 degrees of flexion, no rotation (hips. %)	21 (100)	4 (27)	< 0.001

SCFE indicates slipped capital femoral epiphysis.

with severe SCFE compared with control group (0%, Table 4).

(3) Acetabular impingement conflict was located anterior-superior (between 12 and 3 o'clock, Fig. 2A) in IRF-90 degrees and it was located at 12 o'clock in half of the patients (50%) with severe SCFE (Fig. 2), whereas it was located at 2 o'clock in almost one third (35%, Fig. 2A). This was significantly ($P < 0.001$) different compared with impingement location of the control group.

Femoral impingement in IRF-90 degrees was located on anterior femoral metaphysis (between 2 and 6 o'clock, Fig. 2B), whereas 40% of the patients with severe SCFE showed an impingement on 3 o'clock and another 40% on 5 o'clock (Fig. 2B). This was significantly ($P < 0.001$) different compared with the control group (Fig. 2B) because impingement was mainly (57%) located on 4 o'clock and 21% was located on 3 o'clock, and 14% was located on 5 o'clock. Anterior metaphysis (3 o'clock) is causing impingement conflict before the femoral neck (5 o'clock) is involved (Fig. 3).

Acetabular impingement was mostly located on the anterior-superior rim (70% on 2 o'clock, Fig. 4A) for patients with severe SCFE in maximal flexion (Fig. 5). Femoral impingement was located on the anterior metaphysis (range 1 to 5 o'clock, maximum at 3 o'clock, 40%, Fig. 4B) in maximal flexion and this was significantly decreased compared with the control group (79% was located on 5 o'clock).

DISCUSSION

SCFE can lead to residual deformity associated with FAI and articular cartilage damage.[8] FAI is a known cause for hip pain and precursor to hip osteoarthritis in young patients.[14] Although residual SCFE deformity may partially remodel after in situ pinning,[9] the remodeling process can lead to FAI. Patient-specific 3D models of severe SCFE patients were analyzed to asses hip ROM, frequency of impingement in flexion and acetabular and femoral impingement location. Most importantly, high frequency of impingement in early flexion and limited flexion and IR was found that was significantly ($P < 0.001$) decreased compared with the control group (Table 3). In addition, acetabular impingement location was most often superior (12 o'clock) and anterior-superior (2 o'clock, Fig. 2) in IRF-90 degrees (SCFE patients). Femoral impingement was located anterior-superior to anterior-inferior and femoral metaphysis caused impingement conflict before the femoral neck (Fig. 3).

The literature remains sparse regarding biomechanical analysis of impingement location for SCFE patients.[6,7,10,29] One study evaluated virtual ROM of patients with mild, moderate and severe SCFE without impingement location and reported decreased ROM for increasing severity of SCFE.[7] They evaluated 3D models of 11 hips with severe SCFE and reported lower values for

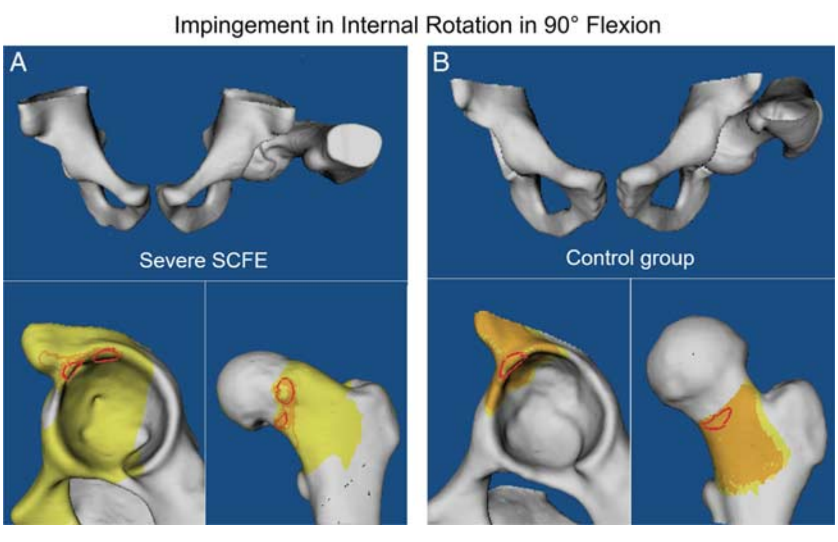

FIGURE 3. Impingement location in 90 degrees of flexion and internal rotation is shown for a patient with severe SCFE (A) and a patient of the control group (B). SCFE indicates slipped capital femoral epiphysis.

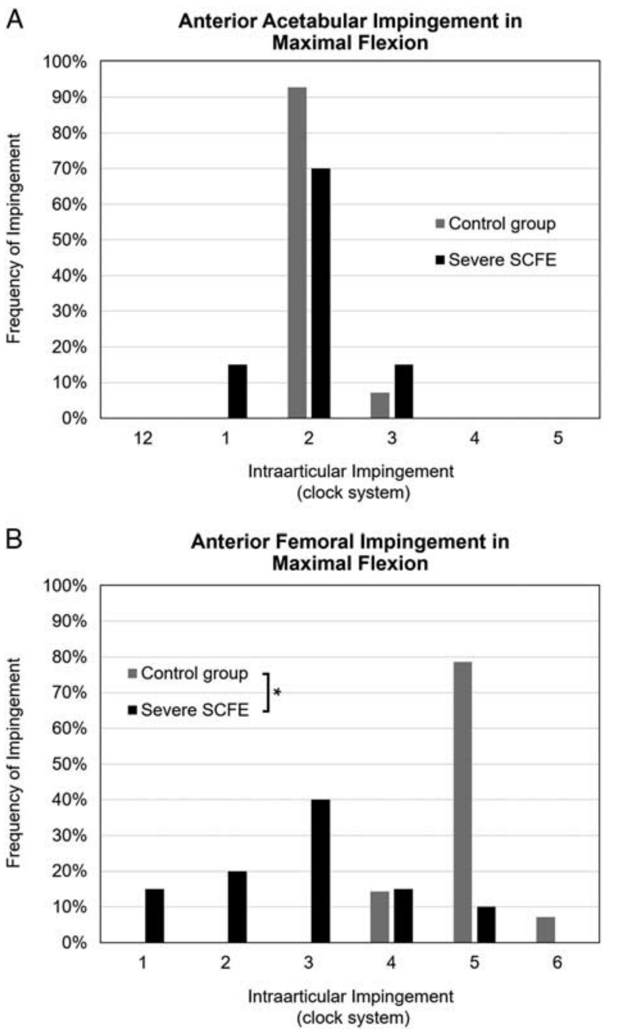

FIGURE 4. A and B, Location of acetabular (A) and femoral (B) impingement in maximal flexion is summarized below for 21 hips of severe SCFE patients. SCFE indicates slipped capital femoral epiphysis.

flexion and IR compared with the current study.[7] A similar study simulated the effect of different proximal femoral osteotomies to improve ROM, unfortunately also without analysis of impingement location.[29] They analyzed 19 patients with moderate or severe SCFE and reported higher ROM values after simulated femoral osteotomies.[29] Comparing ROM, previous studies using bony collision detection software found higher values for IR in 90° of flexion for patients with cam-type or pincer-type FAI.[21,30] In 1999, it was reported that sitting increases hip impingement for SCFE patients[6] and more ER is required for severe slips compared with mild slips. This is consistent with the results found for IR in 30 to 60 and 90 degrees of flexion (Table 3) and for frequency of impingement (Table 4). With increasing flexion (eg, from 30 to 90 degrees), IR decreased from 13 to 17 degrees (Table 3). This means that 17 degrees of ER was needed for impingement-free 90 degrees flexion (Table 3), similar to the Drehmann's sign.[31] More recent studies evaluated patient-specific 3D models for 3D printing[32] or for detailed analysis of the direction of slip.[33] No other study was found that assessed patient-specific location of bony hip impingement in flexion for patients with SCFE. For hips with anterior FAI due to cam or pincer-type morphologies, similar acetabular osseous impingement location was reported on the antero-superior region.[21] Femoral location for SCFE patients was in line with a previous study evaluating impingement in IRF-90 degrees.[21] Unfortunately no other study evaluated impingement conflict in flexion. Intraoperative evaluation of labral and articular cartilage damage was performed previously[8,13] and significant injuries in the anterior-superior acetabulum were reported at time of deformity correction for patients with SCFE. This corresponds to the acetabular impingement location observed in the current study.

A recent study assessing intraoperative location of cartilage lesions in patients with sequelae of SCFE reported anterior and superior-lateral acetabular cartilage lesions.[34] Anterior cartilage lesions are comparable with the found impingement location in the current study. Another recent study[35] evaluated patients with sequelae of SCFE undergoing hip arthroscopy at mean 2 years after initial surgery and reported labrum tears and acetabular chondral damage in the majority of patients. Hip arthroscopy is increasingly being used for treatment of FAI. Although use of hip arthroscopy for treatment of FAI continues to rise, there is no international consensus for the indications for patients with SCFE. In addition, detailed impingement location is unclear for these patients. The results of the current study could be important for patient-specific planning of hip preservation surgery of SCFE patients. Future studies could assess whether hip ROM can be improved with virtual simulation of different surgeries.

This study has limitations. First, the software for collision detection calculates the osseous ROM, without taking into account soft tissue (labrum, muscles or cartilage). This is unavoidable using pelvic CT scans for 3D modeling, and could be integrated using magnetic resonance imaging of the hip[36,37] in the future. Therefore, we believe, that the clinical ROM should be even lower in these patients. However, this is also the case for published ROM results using another software for collision detection.[38] This method has also been applied to patients with severe hip deformities, including developmental dysplasia of the hip,[22] patients with decreased femoral version[20] and hips with post-LCPD deformities.[28] The application of this method to various hip morphologies underlines the validity of the software for collision detection used in the current study. Second, the patients were recruited from a university hospital for hip preservation surgery with limited generalizability. There could be a potential selection bias of complex patients. Third, we did not report on detailed patient-related outcome or clinical follow-up because this was not the aim of this study. However, all patients were symptomatic at time of image acquisition and 95% of them underwent surgical treatment (Table 2). Finally, we did not evaluate the effect of pelvic tilt, which can also affect hip ROM.

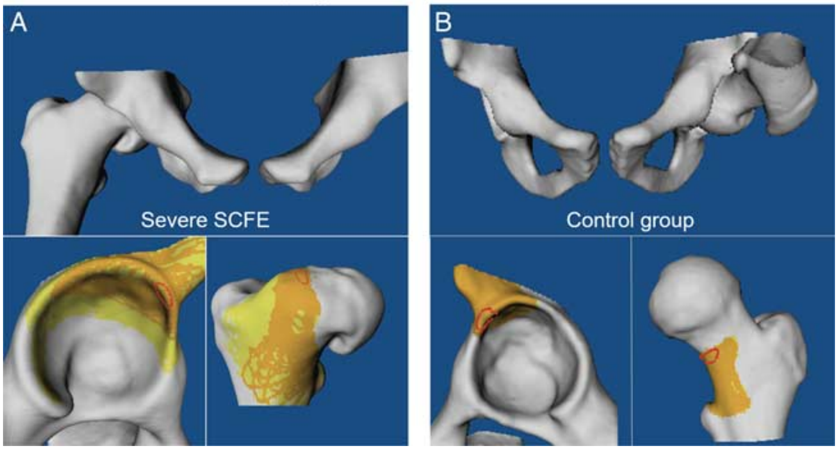

FIGURE 5. Impingement in maximal flexion is shown for a patient with severe SCFE (A) compared with a patient of the control group (B). SCFE indicates slipped capital femoral epiphysis.

CONCLUSION

Patients with severe SCFE had severe limitation of ROM and early hip impingement in flexion using patient-specific preoperative 3D models. Location of exact hip impingement could guide the needed osseous resection or correction for hip preservation surgery. 3D modeling could be useful for preoperative planning and simulation of surgical procedures and for the decision if in situ pinning or proximal femoral osteotomy or modified Dunn procedure should be performed for patients with severe SCFE.

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