Do Osteochondroplasty Alone, Intertrochanteric Derotation Osteotomy, and Flexion-Derotation Osteotomy Improve Hip Flexion and Internal Rotation to Normal Range in Hips With Severe SCFE? - A 3D-CT Simulation Study

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Background: Severe slipped capital femoral epiphysis (SCFE) leads to femoroacetabular impingement and restricted hip motion. We investigated the improvement of impingement-free flexion and internal rotation (IR) in 90 degrees of flexion following a simulated osteochondroplasty, a derotation osteotomy, and a combined flexion-derotation osteotomy in severe SCFE patients using 3D-CT-based collision detection software.

Methods: Preoperative pelvic CT of 18 untreated patients (21 hips) with severe SCFE (slip-angle > 60 degrees) was used to generate patient-specific 3D models. The contralateral hips of the 15 patients with unilateral SCFE served as the control group. There were 14 male hips (mean age 13 ± 2 y). No treatment was performed before CT. Specific collision detection software was used for the calculation of impingement-free flexion and IR in 90 degrees of flexion and simulation of osteochondroplasty, derotation osteotomy, and combined flexion-derotation osteotomy.

Results: Osteochondroplasty alone improved impingement-free motion but compared with the uninvolved contralateral control group, severe SCFE hips had persistently significantly decreased motion (mean flexion 59 ± 32 degrees vs. 122 ± 9 degrees, $P < 0.001$; mean IR in 90 degrees of flexion −5 ± 14 degrees vs. 36 ± 11 degrees, $P < 0.001$). Similarly, the impingement-free motion was improved after derotation osteotomy, and impingement-free flexion after a 30 degrees derotation was equivalent to the control group (113 ± 42 degrees vs. 122 ± 9 degrees, $P = 0.052$). However, even after the 30 degrees derotation, the impingement-free IR in 90 degrees of flexion persisted lower (13 ± 15 degrees vs. 36 ± 11 degrees, $P < 0.001$). Following the simulation of flexion-derotation osteotomy, mean impingement-free flexion and IR in 90 degrees of flexion increased for combined correction of 20 degrees (20 degrees flexion and 20 degrees derotation) and 30 degrees (30 degrees flexion and 30 degrees derotation). Although mean flexion was equivalent to the control group for both (20 degrees and 30 degrees) combined correction, the mean IR in 90 degrees of flexion persisted decreased, even after the 30 degrees combined flexion-derotation (22 ± 22 degrees vs. 36 degrees ± 11, $P = 0.009$).

Conclusions: Simulation of derotation-osteotomy (30 degrees correction) and flexion-derotation-osteotomy (20 degrees correction) normalized hip flexion for severe SCFE patients, but IR in 90 degrees of flexion persisted slightly lower despite significant improvement. Not all SCFE patients had improved hip motion with the performed simulations; therefore, some patients may need a higher degree of correction or combined treatment with osteotomy and cam-resection, although not directly investigated in this study. Patient-specific 3D-models could help individual preoperative planning for severe SCFE patients to normalize the hip motion.

Level of Evidence: III, case-control study

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Each author certifies that his or her institution 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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In slipped capital femoral epiphysis (SCFE), shearing forces surpass the stability of the proximal femoral physis, causing the metaphysis to rotate on the epiphyseal tubercle as a fulcrum, resulting in an extension and a retroversion deformity.[1,2] The resulting deformity is classified based on the head-shaft angle as mild (< 30 degrees), moderate (30 degrees to 60 degrees), and severe SCFE (> 60 degrees).[3] Previous studies suggested that treatment with in-situ fixation is associated with good Iowa hip scores in the long term.[4,5] However, the severity of SCFE deformity is directly related to the development of symptoms and early hip osteoarthritis.[6] SCFE deformity leads to femoroacetabular impingement (FAI), resulting in articular cartilage damage and posing a risk for long-term osteoarthritis.[7–11] Hence, the goals of surgical treatment of SCFE have expanded from the short-term perspective, focusing on stabilizing the physis and preventing further slip, towards a long-term goal to prevent secondary FAI and further osteoarthritis.[12]

Hip arthroscopy is the mainstay of surgical treatment of cam-type FAI, and the role of arthroscopic cam resection of the femoral head-neck junction has been expanded to the treatment of symptomatic residual deformity associated with SCFE.[13–16] However, arthroscopic treatment may be limited to restoring the normal range of motion in hips with severe SCFE.[17] Several femoral osteotomies have been described to improve the alignment of the proximal femur in hips with residual deformity due to severe SCFE, including the Imhauser flexion-derotational intertrochanteric osteotomy,[18] the Southwick triplane proximal osteotomy,[3] an osteotomy at the base of the femoral neck,[19,20] the femoral neck closing wedge osteotomy according to Dunn[21] and Fish,[22] a simple diaphyseal derotation osteotomy with intramedullary fixation.[23] More recently, the modified Dunn procedure using the surgical hip dislocation approach has gained popularity because of the possible complete restoration of the proximal femoral anatomy and improved outcomes.[24–27] However, this procedure is not widely available, and indications are discussed controversially. Therefore, proximal femoral osteotomies still play an important role in treatment. Nevertheless, independent of the treatment used, deformity correction of severe SCFE is challenging due to its 3-dimensional complexity.[1,28–31] Although 2-dimensional radiographs are used to diagnose SCFE, the head-neck angle measurement, and SCFE classification are affected by the patient's position, and radiographs do not allow for a comprehensive deformity analysis.[32] Previous studies have described the application of 3D-CT for surgical planning.[33] However, its application remains restricted due to radiation exposure.

This study investigates the improvement of impingement-free motion following a simulated osteochondroplasty, a derotation-osteotomy, and a combined flexion-derotation osteotomy in hips with untreated severe SCFE using 3D-CT and collision detection software.

METHODS

Study Population

After obtaining institutional review board approval, we identified 123 patients treated for SCFE who underwent a pelvic CT between 1998 and 2016. Out of 123 patients with CT scans, we excluded 105 patients due to a mild or moderate SCFE, postoperative CT, and those with CT that did not involve the femoral condyles. The study cohort comprised 18 patients with severe SCFE (slip angle > 60 degrees), and preoperative CT was used to generate patient-specific 3D models. Of the 18 patients, no previous treatment was noted. Three patients (15%) had bilateral SCFE yielding a total of 21 hips evaluated. The contralateral hips of the 15 patients with unilateral SCFE were used as a control group. The mean age was 13 years (SD, ± 2 y, Table 1). There were 14 male hips, and the mean body mass index (BMI) was 28 ± 5. Seventeen (81%) hips were further classified as chronic (> 3 wk of symptoms), while the remaining were considered acute on chronic (> 3 wk of prodrome symptoms but with acute exacerbation in the last 3 wk). Eighteen out of the 21 hips (86%) were stable, and 3 hips were unstable slips, according to the Loder et al[34] classification system (Table 1).

Imaging, Bone Segmentation, and 3D Modeling

All patients underwent standardized AP, lateral radiographs, and CT scans, including the bilateral hip joint and the distal femoral condyles. CT scan was performed to assess SCFE severity, to measure the femoral version, and for surgical planning. Following

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 (years)	13 ± 2 (10–16)
Sex (% male of all hips)	10 hips, 48
Side (% left of all hips)	12 hips, 57
Height (cm)	166 ± 9 (152–179)
Weight (kg)	80 ± 12 (53–97)
Body mass index (kg/m^2)	28 ± 5 (22–36)
BMI percentile	93
Unstable hips according to Loder classification (% unstable of all hips)[34]	3 hips, 14
Severity based on slip Angle[3] (% of all hips)	
Mild <30 (deg)	0
Moderate 30–60 (deg)	0
Severe > 60 (deg)	21 hips, 100
Classification based on the duration of symptoms (% of all hips), 52	
Acute	0
Acute on chronic	4 hips, 19
Chronic	17 hips, 81

Continuous values are expressed as mean ± SD, and range in parenthesis the segmentation of CT images, we built a 3D virtual bone model (Fig. 1) of the pelvis and the femur for each hip using the Amira Visualization Toolkit (Visage Imaging Inc, Carlsbad, CA). Computer-assisted bone segmentation was performed by 2 independent observers not involved in the surgical care of the patients (TL and AB).. All 3D models were available from a previous study.[35] Limited Hip Flexion and Internal Rotation Resulting From Early Hip Impingement Conflict on Anterior Metaphysis of Patients With Untreated Severe SCFE Using 3D Modelling (TL and AB). The reference coordinate system for the acetabulum was the anterior pelvic plane (APP), defined by both anteroinferior iliac spines and the pubic tubercles, and for the femur, it was defined by the center of the femoral head, the knee center, and both femoral condyles as previously described.[36]

Simulation of Hip Impingement and Surgery

The virtual 3D bone models (Fig. 1) were exported to specific software for collision detection and quantification of impingement-free hip range of motion. This software was previously validated and allowed to simulate human hip motion using CT scans of plastic and cadaveric hips.[36] The software uses the so-called equidistant method, a hip simulation algorithm that accounts for a dynamic hip joint center and allows to calculate the hip range of motion with a higher linear and angular accuracy compared with other methods.[37]

Hip flexion and internal rotation (IR) in 90 degrees of flexion were simulated using the CT-based 3D models, and the impingement-free flexion and impingement-free IR in 90 degrees of flexion were recorded for the untreated severe SCFE hips. Impingement-free motion was assessed by the patient-specific initial point of impingement, defined as the amount of flexion and internal rotation recorded at initial detection of collision between the acetabular rim and the proximal femur. The effect of each specific surgical intervention on the impingement-free flexion and IR in 90 degrees of flexion was calculated and compared with the impingement hip motion before the intervention for the hips with severe SCFE and to the contralateral uninvolved hips as a control group.

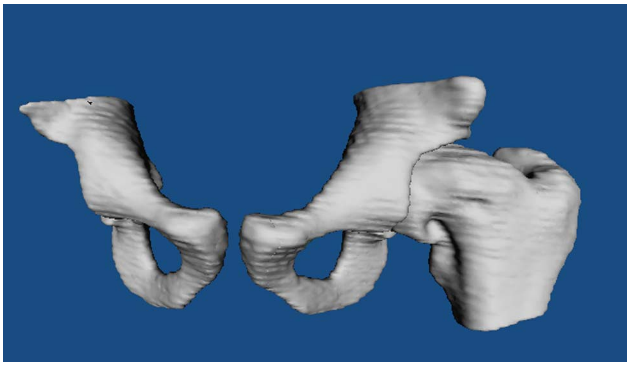

FIGURE 1. A virtual CT-based 3D model of a severe slipped capital femoral epiphysis patient is shown.

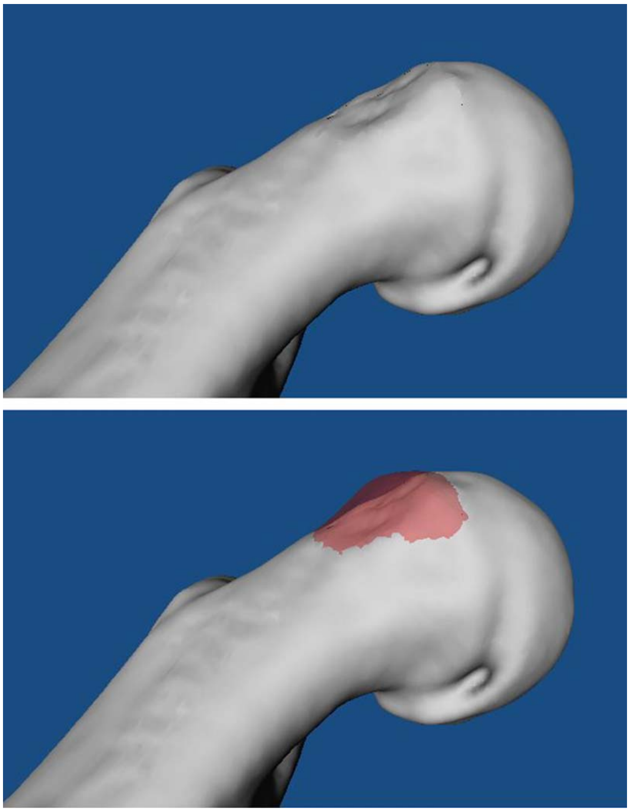

FIGURE 2. A femoral 3D model of a severe slipped capital femoral epiphysis patient after virtual cam resection is shown above. Below the resected bone volume is shown red transparent.

The femoral 3D models were used to simulate osteochondroplasty of the femoral head-neck junction (cam resection, Fig. 2 and figures in supplementary material, Supplemental Digital Content 1, http://links.lww.com/BPO/A583) as previously described by Ecker et al.[38] computer-assisted femoral head-neck osteochondroplasty using a surgical milling device an in vitro accuracy study. Briefly, the software was used to plan and perform repeated computer-assisted osteochondroplasty (cam resection, Fig. 2) using a virtual burr (surgical reaming device, similar to the electric pen drive of Synthes AG, Switzerland). The virtual sphere of the burr was used in a stepwise fashion while the extent and depth of the resection was visualized (red transparent in Fig. 2 and in figures in supplementary material, Supplemental Digital Content 1, http://links.lww.com/BPO/A583) with the goal to improve the femoral head-neck offset. Simulation of virtual surgeries was performed by a resident with 5 y of experience in hip impingement simulation and 5 y of experience in musculoskeletal imaging.

For the simulation of a derotation osteotomy (Fig. 3A), a virtual intertrochanteric osteotomy was performed using the software (figures in supplementary material, Supplemental Digital Content 1, http://links.lww.com/BPO/A583). The landmarks and the reference system used are the same as for the equidistant method.

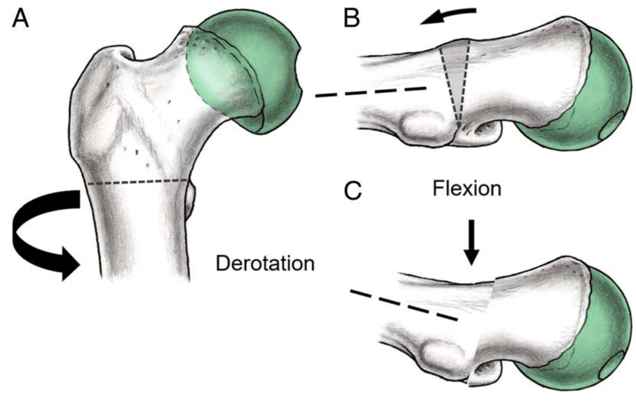

FIGURE 3. A-C. Schematic views of femoral derotation (A) and flexion-derotation-osteotomy (B and C) are shown.

After performing the virtual osteotomy perpendicular to the femoral shaft axis, the distal femur is rotated inwards (medial, in the anterior direction of the contralateral limb) to increase the femoral version. Three virtual femoral derotation osteotomies were created for each patient (1 model for 10 degrees 1 model for 20 degrees and 1 model for 30 degrees of correction, figures in supplementary material, Supplemental Digital Content 1, http://links.lww.com/BPO/A583) as described by Stevens et al.[23] Then, the postoperative 3D models were compared with the preoperative 3D models to calculate the improvement in hip motion and to the control group (Fig. 4).

Finally, we used the software to simulate a flexion derotation osteotomy as described by Imhauser.[18] Using the virtual femoral 3D model of the severe SCFE hips, the flexion derotation intertrochanteric osteotomy (Fig. 3) was simulated with 10 degrees of derotation correction and 10 degrees of flexion correction. A second and a third simulation was performed with 20 degrees of derotation and 20 degrees of flexion and with 30 degrees of derotation and 30 degrees of flexion, respectively. The flexion component of the osteotomy was created by manipulating the distal femoral segment in an anterior direction according to the desired flexion correction, simulating an anterior wedge resection (Fig. 3). We then compared the impingement-free range of motion to the baseline measurements for each patient and to the contralateral uninvolved hip (Fig. 5).

Statistical Analysis

Statistical analysis was performed using Winstat software (R. Fitch software, Bad Krozingen, Germany). Normal distribution was tested using the Kolmogorov-Smirnov test. Because the data were not normally distributed, we only used nonparametric tests. Continuous variables were compared using the Friedman test and the Wilcoxon test because the data were not normally distributed. For the range of motion testing, the baseline (preoperative) range of motion was compared with (1) cam resection, (2) derotation osteotomy for 10 degrees correction, (3) 20 degrees correction, (4) derotation 30 degrees correction, (5) derotation, and flexion 10 degrees, 6) derotation and flexion 20 degrees, and (7) derotation and flexion 30 degrees. Because of the 7 subgroups, the level of significance was adjusted with the Bonferroni correction after counselling a statistician. This is a simple method for adjustment. The level of significance was $0.05/7 = 0.0071$. This means a P value below 0.0071 was considered significant.

RESULTS

The impingement-free motion was limited in the hips with severe SCFE at baseline (Table 2). The mean impingement-free flexion (46 ± 32 degrees vs. 122 ± 9 degrees, $P < 0.001$) and mean impingement-free IR in 90 degrees of flexion (-17 ± 18 degrees vs. 36 ± 11 degrees, $P < 0.001$) were significantly decreased in the severe SCFE hips compared with the contralateral control hips (Table 2).

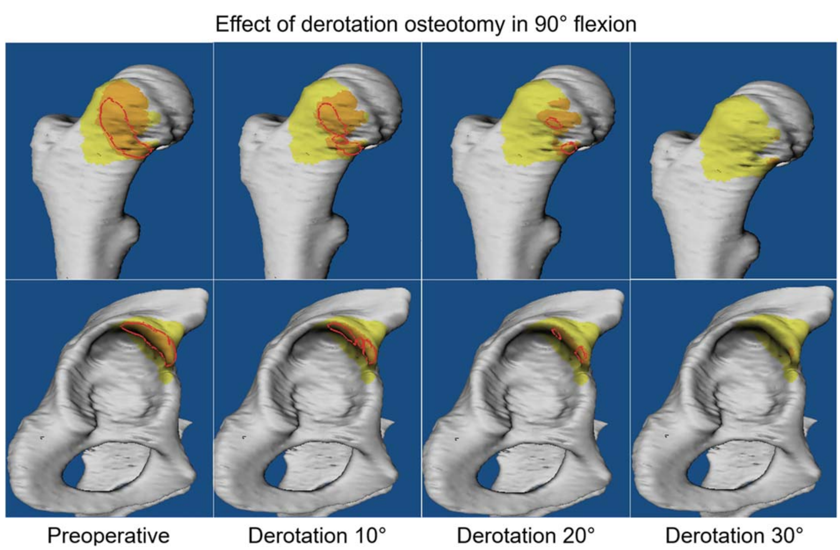

FIGURE 4. Simulation of femoral derotation osteotomy to increase femoral version is shown for a severe slipped capital femoral epiphysis patient. The red zone represents the impingement zone. No impingement was noted after 30 degrees of derotation.

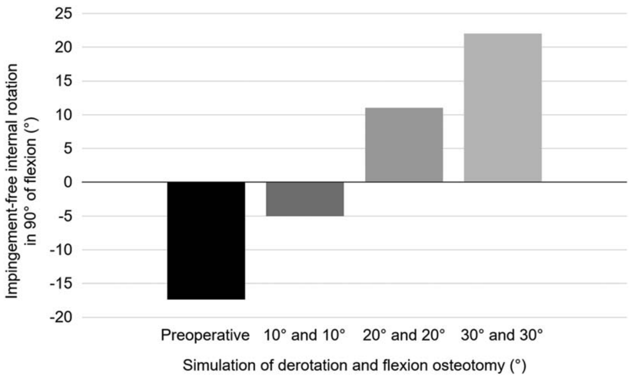

FIGURE 5. Simulation of combined flexion and derotation osteotomy is shown for internal rotation in 90 degrees of flexion.

Simulation of motion after osteochondroplasty compared with the baseline motion of the severe SCFE hips showed improvement in impingement-free flexion (59 ± 32 degrees, range 0 to 121 degrees vs. 46 ± 32 degrees; $P<0.001$) and impingement-free IR in 90 degrees of flexion (–5 ± 14 degrees, range −50 to 19 degrees vs. −17 ± 18 degrees, $P=0.002$). However, when compared with the contralateral control group, the hip motion of severe SCFE hips after osteochondroplasty (Fig. 2) was significantly decreased (mean flexion 59 ± 32 degrees vs. 122 ± 9 degrees, $P<0.001$ and mean IR in 90 degrees of flexion (−5 ± 14 degrees vs. 36 ± 11 degrees, $P<0.001$).

After derotation-osteotomy (Fig. 4), mean impingement-free flexion increased significantly with 10, 20 and 30 degrees of correction ($P<0.001$, Table 2). However, mean impingement-free IRF-90 degrees was not improved after 10 degrees correction but significantly ($P<0.001$) improved to 3 ± 15 degrees and 13 ± 15 degrees (Table 2) with 20 and 30 degrees of simulated derotation ($P<0.001$), respectively. The mean impingement-free flexion after a 30 degrees derotation was not different compared with the control group (113 ± 42 degrees vs. 122 ± 9 degrees; $P=0.052$). However, after the 30 degrees derotation, the impingement-free IRF-90 degrees persisted lower compared with the control group (13 ± 15 degrees vs. 36 ± 11 degrees, $P<0.001$).

Following the simulation of the flexion-derotation osteotomy (Fig. 5), mean impingement-free flexion increased significantly ($P<0.001$) for the 10, 20, and 30 degrees of combined correction (eg, to 138 ± 47 degrees for the 30 degrees combined correction, Table 3). Mean impingement-free IR in 90 degrees of flexion did not improve significantly ($P<0.001$) with the 10 degrees combined correction but improved after the 20 and 30 degrees combined correction. (Table 3) When compared with the contralateral uninvolved control hips, mean flexion was no different for the 20 degrees combined correction (119 ± 45 degrees vs. 122 ± 9 degrees; $P=0.052$). However, the mean impingement-free IR in 90 degrees of flexion persisted decreased after the 30 degrees combined flexion-derotation when compared with the contralateral uninvolved control hips (22 ± 22 degrees vs. 36 degrees ± 11, $P=0.009$).

DISCUSSION

We compared the improvement of impingement-free flexion and IR in 90 degrees of flexion following simulated osteochondroplasty of the femoral head-neck junction, femoral derotation-osteotomy, and combined flexion-derotation-osteotomy in hips with severe SCFE (Fig. 3) to the contralateral uninvolved hips using specific software for collision detection. Although osteochondroplasty improved the limited hip motion, the achieved range of impingement-free motion was far from the normal hip motion simulated for the contralateral uninvolved hips. Similar findings were noted for improving impingement-free motion following a derotation osteotomy of 10 and 20 degrees and even after a flexion-derotation osteotomy with 10 degrees combined correction. A 30 degrees derotation osteotomy (Fig. 4) improved hip flexion to no difference compared with the contralateral uninvolved hip, but with persistent limited IR in 90 degrees of flexion (Table 2).

We found that simulated osteochondroplasty of the femoral head and neck junction did not normalize impingement-free motion as compared with the contralateral uninvolved control hips. Along the same lines, Wylie et al[17] compared the functional results of arthroscopic treatment with osteochondroplasty versus open surgical treatment through a surgical hip dislocation with or without a femoral osteotomy. They suggested arthroscopic osteochondroplasty to treat hips with mild SCFE deformity and only slightly limited hip IR in 90 degrees of flexion. Patients with severe SCFE deformity with obligatory external rotation in flexion benefit from a flexion-derotation osteotomy to improve the range of impingement-free motion. Besomi et al[14] reported on the results of hip arthroscopy treatment, including osteochondroplasty in 17 patients with residual SCFE deformity, and found only 6 degrees of hip flexion and 14 degrees of IR improvement. Balakumar et al[37] reported a less significant improvement of hip IR for patients with severe and moderate SCFE deformity treated with ar-

TABLE 2. Virtual Treatment Simulation of 21 Hips with Untreated Severe SCFE Using Preoperative 3D-CT

Parameter	No treatment	Derotation 10 (deg)	Derotation 20 (deg)	Derotation 30 (deg)
Flexion	46 ± 32 (0 to 113)	79 ± 44 (10 to 130)*	103 ± 43 (14 to 150)*	113 ± 42 (19 to 160)*
Internal rotation in 90 degrees of flexion (deg)	−17 ± 18 (−60 to 10)	−7 ± 15 (−53 to 15)	3 ± 15 (−43 to 25)*	13 ± 15 (−33 to 35)*

*signifies significant difference compared with no treatment, P values below 0.0071 were considered significant.
level of significance was adjusted with the Bonferroni correction to 0.05/7 = 0.0071.
Derotation osteotomy was simulated to increase femoral version.

TABLE 3. Virtual Treatment Simulation of 21 Hips with Untreated Severe SCFE Using Preoperative 3D-CT

Parameter	No treatment	Derotation 10 and Flexion 10 (deg)	Derotation 20 and Flexion 20 (deg)	Derotation 30 and Flexion 30 (deg)
Flexion	46 ± 32 (0 to 113)	86 ± 45 (10 to 139)*	119 ± 45 (14 to 160)*	138 ± 47 (39 to 180)*
Internal rotation in 90 degrees of flexion (deg)	−17 ± 18 (−60 to 10)	-5 ± 15 (−50 to 29)	11 ± 21 (−47 to 37)*	22 ± 22 (−40 to 49)*

*signifies significant difference compared with no treatment, P values below 0.0071 were considered significant.
level of significance was adjusted with the Bonferroni correction to 0.05/7 = 0.0071.
Flexion and derotation osteotomy was simulated to increase femoral version.

throscopic osteochondroplasty (mean improvement 20 degrees, range 0 to 20 degrees) compared with open femoral neck osteotomy (mean improvement 50 degrees, range 30 to 70 degrees). Based on our findings and previous studies, isolated osteochondroplasty improves hip motion in hips with severe SCFE; the improvement, however, is modest and insufficient to restore impingement-free motion.

In this study, we observed significant improvement in impingement-free flexion and IR in 90 degrees of flexion following an isolated derotation osteotomy of the femur when we simulated a 30 degrees correction. Although correcting femoral retroversion is a component of most femoral osteotomies independent of the correction level, applying a pure derotation osteotomy to the treatment of FAI secondary to SCFE is relatively novel. Stevens et al[23] described a femoral midshaft 45 degrees derotation osteotomy fixed with an intramedullary nail in 4 patients with severe residual SCFE deformity. They reported significant improvement in hip flexion, IR, and gait analysis. However, 2 patients required secondary arthroscopic osteochondroplasty to alleviate residual FAI, and 1 patient underwent a total hip replacement 62 months after the osteotomy. In addition, 2 patients had delayed union and some loss of correction, secondary to broken interlocking screws, and required revision surgery with reaming and nail exchange. Although our study confirms that a 30 degrees simple derotation osteotomy may normalize hip flexion, future studies are necessary to determine the clinical and functional outcomes of a pure derotation osteotomy and to define the specific preoperative criteria for the indication of this procedure. Applying collision detection software may enhance the ability of the treating surgeon to determine the amount of retroversion correction during surgery. Further steps are needed to apply this software in clinical practice; so far the software has been used for research purposes only (figures in supplementary material, Supplemental Digital Content 1, http://links.lww.com/BPO/A583).

Simulation of hip range of motion and evaluation of different techniques of femoral osteotomy to assess the improvement in range of hip motion and the hip-joint geometry is not a novel concept, but the literature is scarce.[31,40,41] One previous study evaluated 3D models of 11 hips with severe SCFE and reported lower values for flexion and IR compared with the current study.[31] Mamisch et al[41] simulated the effect of a multiplanar Southwick[3] intertrochanteric osteotomy with flexion, valgus, and IR to a uniplanar purely flexion osteotomy. They analyzed 19 patients with moderate or severe SCFE and reported lower values for hip flexion and IR (61 and 66 degrees) after the simulation of a multiplanar femoral intertrochanteric osteotomy and the simulation of uniplanar flexion osteotomy (63 and 54 degrees). Interestingly, they found similar improvements in hip motion (apart from abduction) for both multiplanar and uniplanar femoral osteotomy. One advantage of the collision detection software used in the current study is the ability to determine the patient-specific impingement-free range of motion of the hip joint.

This study has several limitations. First, the software for collision detection calculates the osseous range of motion without considering soft tissue (labrum, ligaments, or cartilage). Therefore, we believe the clinical hip motion may be even lower in these hips. Assessment of the soft tissues limiting motion may be unavoidable using pelvic CT imaging, although it could be integrated using magnetic resonance imaging in the future. However, previous collision detection studies used the same specific software to analyze hips with complex morphology, including post-Perthes disease, underlining the software's validity for collision detection in hips with severe deformity. Second, we only tested 3 types of surgical intervention (osteochondroplasty, femoral derotation osteotomy, and flexion-derotation osteotomy, figures in supplementary material, Supplemental Digital Content 1, http://links.lww.com/BPO/A583). Other types of proximal femoral osteotomies could result in more significant improvement in impingement-free motion. No translation was performed for the flexion osteotomy. The rationale for selecting the 3 specific surgical interventions was based on the increased popularity of arthroscopic osteochondroplasty for treating hips with SCFE and the fact that femoral derotation osteotomy is a universally available and relatively low-demanding technique. Similarly, the flexion-derotation osteotomy is a well-accepted procedure for treating SCFE deformity that is technically less demanding than some of the procedures we did not test (eg, the modified Dunn procedure). Third, our study focused on the simulated surgical procedure without assessing the actual results of such procedures. No postoperative alpha angles after cam resection were calculated because of the severe displacement of the epiphysis and the femoral head center. Therefore, we lack information about those procedures' complications and clinical improvement. Although comparing patient-specific interventions and outcomes was not the goal of our study, all patients were symptomatic at the time of image acquisition, and most of them underwent surgical treatment. Therefore, future studies should investigate the simulation of additional isolated or combined hip preservation procedures to investigate clinical and functional improvements of such procedures to establish the clinical application of the software in the clinical setting. A combination of femoral osteotomy and cam resection was not studied and could be an additional treatment approach for severe SCFE patients. Finally, our study was limited to hips with severe SCFE, and we cannot make any inference about the effects of the investigated procedures on the improvement of hip motion for hips with mild and moderate SCFE.

Preoperative planning is crucial before surgical corrections in patients with severe SCFE. The severity of the femoral deformity and the morphology of the acetabulum vary between patients resulting in complex FAI. Although femoral derotation osteotomy (30 degrees correction) or combined flexion and derotation osteotomy (20 degrees correction) enabled the restoration of impingement-free flexion, similar to the hip flexion of the control group, IR in 90 degrees of flexion remained lower than the control group, despite significant improvement. Furthermore, not all severe SCFE hips achieved normal motion after the simulation of derotational and flexion-derotation osteotomy (Figs. 3 and 4). Patient-specific 3D models and virtual surgical simulation provide a unique opportunity to understand the deformity better and determine the personalized bony correction needed to optimize impingement-free motion in patients with severe SCFE, but future studies should determine whether preoperative simulation and planning impact patient-specific symptoms and hip function.

CONCLUSION

Simulation of derotation-osteotomy (30 degrees correction) and flexion-derotation-osteotomy (20 degrees combined correction) normalized hip flexion for severe SCFE patients, but IR in 90 degrees of flexion persisted slightly lower despite significant improvement. Not all SCFE patients had improved hip motion with the performed simulations; therefore, some patients may need a higher degree of correction or combined treatment with osteotomy and cam-resection, although not directly investigated in this study. Patient-specific 3D models could help individual preoperative planning for severe SCFE patients to normalize hip motion.

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