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HIP

Femoral impingement in maximal hip flexion is anterior-inferior distal to the cam deformity in femoroacetabular impingement patients with femoral retroversion

IMPLICATIONS FOR HIP ARTHROSCOPY

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Aims

Femoroacetabular impingement (FAI) patients report exacerbation of hip pain in deep flexion. However, the exact impingement location in deep flexion is unknown. The aim was to investigate impingement-free maximal flexion, impingement location, and if cam deformity causes hip impingement in flexion in FAI patients.

Methods

A retrospective study involving 24 patients (37 hips) with FAI and femoral retroversion (femoral version (FV) < 5° per Murphy method) was performed. All patients were symptomatic (mean age 28 years (SD 9)) and had anterior hip/groin pain and a positive anterior impingement test. Cam- and pincer-type subgroups were analyzed. Patients were compared to an asymptomatic control group (26 hips). All patients underwent pelvic CT scans to generate personalized CT-based 3D models and validated software for patient-specific impingement simulation (equidistant method).

Results

Mean impingement-free flexion of patients with mixed-type FAI (110° (SD 8°)) and patients with pincer-type FAI (112° (SD 8°)) was significantly ($p < 0.001$) lower compared to the control group (125° (SD 13°)). The frequency of extra-articular subspine impingement was significantly ($p < 0.001$) increased in patients with pincer-type FAI (57%) compared to cam-type FAI (22%) in 125° flexion. Bony impingement in maximal flexion was located anterior-inferior at femoral four and five o'clock position in patients with cam-type FAI (63% (10 of 16 hips) and 37% (6 of 10 hips)), and did not involve the cam deformity. The cam deformity did not cause impingement in maximal flexion.

Conclusion

Femoral impingement in maximal flexion was located anterior-inferior distal to the cam deformity. This differs to previous studies, a finding which could be important for FAI patients in order to avoid exacerbation of hip pain in deep flexion (e.g. during squats) and for hip arthroscopy (hip-preservation surgery) for planning of bone resection. Hip impingement in flexion has implications for daily activities (e.g. putting on shoes), sports, and sex.

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Keywords: FAI, Femoroacetabular impingement, Extra-articular hip impingement, Subspine impingement, Hip arthroscopy, Hip preservation surgery

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Article focus

- The aim was to investigate impingement-free maximal flexion, impingement location, and if cam deformity causes hip impingement in flexion in FAI patients with femoral retroversion.

Key messages

- Femoral impingement conflict in flexion was located anterior-inferior, distal to the cam deformity.
- Cam deformity was not involved in maximal flexion without rotation.
- Hip impingement in flexion has implications for squats, sports, and sex.

Strengths and limitations

- Personalized CT-based 3D models and validated software were used for patient-specific impingement simulation.
- Only bone-to-bone impingement conflict was investigated; no soft-tissue (labrum or cartilage) was investigated.

Introduction

Patients with femoroacetabular impingement (FAI) often have limited hip function and capacity to participate in sports.[1,2] FAI patients report symptom onset to be insidious and activity-related.[1,3] Exacerbation of groin pain with squatting or sitting was reported; some patients were limited to sitting for less than 30 minutes.[3] In addition, almost one-third (31%) of FAI patients reported difficulties with putting on shoes and socks.[3] Theoretically, this could be due to reduced flexion or hip impingement in flexion. Squat kinematics have been investigated previously,[4] and FAI surgery can improve squatting depth.[5] Unfortunately, one previous study that investigated impingement conflict in maximal flexion, or in sitting position and other hip motion in everyday life, involved patients without cam-type FAI.[6]

FAI can result from osseous abnormalities of the proximal femur and/or the acetabulum,[7] and was initially classified into two broad categories, namely cam (femoral) and pincer (acetabular) type.[7,8] More recently, abnormal acetabular and femoral version (FV) was found to be combined with FAI morphologies,[9] and both influence hip range of motion (ROM).[10,11] Abnormalities of FV were found in patients with FAI and could be contributing factors to the development of hip pain.[2,9] A previously published study demonstrated that both FV and abnormalities of acetabulum play an important role, and can influence patient-related outcomes after hip arthroscopy for FAI.[12]

After description of cam-type FAI, there was a large increase in hip arthroscopy in order to treat FAI.[13] While use of hip arthroscopy for treatment of FAI continues to rise, the exact location of bony hip impingement in flexion is unknown for FAI patients, and also for patients with femoral retroversion. Prior studies showed that symptomatic FAI patients have decreased flexion,[14,15] in addition to decreased internal rotation (IR) in 90° of flexion.[16] Reduced flexion and an impingement conflict between the proximal femur and the anterior iliac inferior spine (AIIS, so-called subspine impingement) in combined flexion and IR was described in patients with decreased FV. In one study, cam deformities were associated with decreased flexion.[17] However, the location of hip impingement conflict in flexion is unclear in FAI patients.[18] Theoretically, this could be important for surgical treatment with cam resection during hip arthroscopy for patients with hip pain while squatting or sitting. In patients with decreased FV, the exact femoral and acetabular locations of hip impingement in deep flexion (or maximal flexion) are unknown.

Therefore, the aims of the study were to investigate: 1) impingement-free maximal flexion; 2) location of intra- or extra-articular impingement in flexion; and 3) if cam-deformity causes impingement in flexion in symptomatic FAI patients with decreased FV.

Methods

An institutional review board-approved retrospective controlled study was performed, involving 37 hips of 24 symptomatic patients with anterior FAI and decreased FV. Of these, subgroups with cam- or pincer-type FAI were compared. All patients with FAI were symptomatic and had anterior hip pain and a positive anterior impingement test. Of the 37 hips with decreased FV, 16 hips had cam-type deformity (Table I).

Group allocation. All symptomatic FAI patients included in this study presented in our outpatient clinic between January 2014 and December 2016 and were retrospectively reviewed. They presented with anterior hip/groin pain, with a positive anterior impingement test and decreased flexion and internal rotation during clinical examination. All symptomatic FAI patients included in this study underwent pelvic CT scans (acquired in supine position) and had FV < 5°.

Inclusion criteria for FAI patients were symptomatic patients (groin pain) and no advanced osteoarthritis in the presence of normal acetabular coverage or overcoverage and FV < 5°. Exclusion criteria were as follows: a lateral-centre edge angle (LCEA) of < 22°,[20] or an acetabular index > 14°,[21] and osteoarthritis Grade 1 or higher according to Tönnis.[22] This resulted in patient series of 37 hips in 24 symptomatic FAI patients (Table I). They were mainly male patients (69%) with a mean age of 28 years (standard deviation (SD 9) (Table I). All 37 hips were included in a previous investigation.[19] On MRI, some of these patients exhibited an anterior labrum tear. Of the 37 hips, 16 hips had cam-type deformity, seven hips had pincer-type deformity, six hips had mixed-type FAI, and eight hips had neither a cam nor a pincer-type deformity. Surgical treatment was performed in half of the patients (49%, n = 18 hips) at the time of data collection. Surgical treatment was mostly performed with hip arthroscopy or open surgical hip dislocation for combined femoral cam resection and acetabular rim trimming.

Table I. Demographic and radiological description of the study groups is shown. Reprinted and adapted with permission from Lerch et al.[19]

Parameter	Mixed FAI and FV < 5°	Pincer FAI and FV < 5°	Cam FAI and FV < 5°
Hips (patients), n	6 (3)	7 (5)	16 (11)
Mean age, yrs (SD, range)	31 (7, 22 to 37)	32 (9, 22 to 47)	27 (10, 18 to 54)
Sex (% male)	83 (5 hips)	57 (4 hips)	63 (10 hips)
Side (% right)	83 (5 hips)	57 (4 hips)	50 (8 hips)
Mean height, cm (SD, range)	182 (8, 173 to 194)	174 (10, 162 to 187)	174 (6, 162 to 185)
Mean weight, kg (SD, range)	86 (16, 75 to 118)	88 (10, 76 to 100)	76 (10, 59 to 94)
Mean BMI, kg/m^2 (SD, range)	26 (3, 23 to 31)	29 (4, 23 to 34)	25 (4, 19 to 33)
Mean LCE angle, ° (SD, range)	39 (5, 36 to 48)	40 (4, 36 to 47)	27 (6, 19 to 35)
Mean neck-shaft angle, ° (SD, range)	125 (10, 111 to 137)	127 (5, 121 to 135)	131 (5, 121 to 138)
Crossover sign (%)	83 (5 hips)	43 (3 hips)	38 (6 hips)
Posterior wall sign (%)	100 (6 hips)	71 (5 hips)	50 (8 hips)
Mean α angle, ° (SD, range)	61 (4, 56 to 68)	48 (4, 45 to 54)	61 (3, 57 to 67)
Mean femoral version, ° (SD, range)	0 (5, -8 to 4)	3 (2, -1 to 4)	0 (4, -8 to 5)
Mean acetabular version, ° (SD, range)	12 (4, 7 to 16)	12 (5, 6 to 18)	14 (4, 8 to 25)
Mean combined version, McKibbin index, ° (SD, range)	10 (6, 0 to 17)	13 (8, 0 to 20)	15 (6, 5 to 27)

FAI, femoroacetabular impingement; FV, femoral version; LCE, lateral centre edge; SD, standard deviation.

Table II. Definition of the radiological parameters and subtypes of FAI are shown below. Reprinted with permission from Lerch et al.[29]

Parameter	Definition
Subtype of FAI	
Cam-type FAI	α angle > 50°[25] with normal acetabular coverage (LCEA 23° to 33°)[20]
Mixed-type FAI	α angle > 50°[25] and LCEA > 34°
Pincer-type	Overcoverage: LCEA 34° to 39°[20] with α angle < 50°, severe overcoverage: LCEA > 39°,[21] and/or protrusio acetabuli (defined as femoral head touching or crossing the ilioischial line)
Exclusion criteria	
Hip dysplasia	LCEA < 22°[20]

FAI, femoroacetabular impingement; LCEA, lateral centre-edge angle.

The control group of asymptomatic hips underwent pelvic CT scans. The 26 hips of the control group were selected from the contralateral hips of 146 patients undergoing CT-based computer-assisted THA in another institution and were considered normal. Hips with the following features were excluded: THA or TKA, hip pain, previous hip surgery, osteoarthritis Grade 1 or higher according to Tönnis,[22] LCEA of less than 22°, pistol grip deformity,[23] coxa profunda, coxa vara or valga, acetabular or femoral retroversion,[18,24] protrusio acetabuli, and α angle of more than 50°. The control group had normal mean α angle of 42° and normal mean LCEA of 32°. FV of the control group lies in the normal range of 10° to 25°. The control group was available from a previous study,[19] and 3D-CT and 3D models of this group were previously evaluated. Due to the time-consuming process of bone segmentation and impingement simulation of patient-specific 3D models of the hip joint, these hips were used again in this study.

Imaging. Cam-type morphology was defined as an α angle[25] above 50° on lateral radiographs. Pincer-type morphology was defined as a LCEA above 34°,[20] with an α angle < 50° (Table II). A mixed-type morphology was defined as the combination of an α angle > 50° and a LCEA > 34° (Table II). Images of axial CT scans on the level of the femoral head centre were used for calculation of acetabular version.[21] Measurement of FV was performed on standardized pelvic CT scans according to the method described by Murphy et al.[26] This measurement method showed a higher accuracy and smaller variability using CT scans compared to biplane radiographs.[27] Decreased FV was defined as FV < 5°. One observer (TDL) evaluated the morphology of the AIIS spine with 3D reconstructions using a published classification system.[28] None of the FAI patients had type 3 AIIS morphology; such morphology is important and could influence the occurrence of subspine impingement. A higher rate of subspine impingement was reported previously for patients with type 3 AIIS morphology.[28]

All patients underwent standardized AP and lateral radiographs, and CT scans including the entire pelvis and the distal femoral condyles. Then, bone segmentation was performed to generate a 3D surface model of the pelvis and the femur (proximal and distal femur) using the Amira Visualization Toolkit (Visage Imaging Inc, USA). The methods for 3D modelling and impingement simulation were previously reported.[19,29,30] Before motion was simulated, the neutral position of the pelvis was defined using the anterior pelvic plane

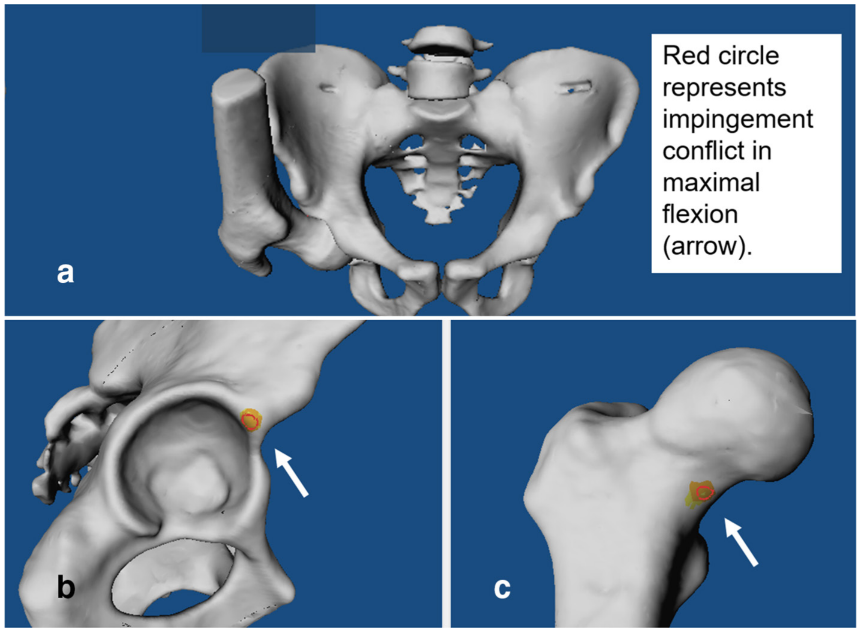

Fig. 1

a) CT-based 3D model of the pelvis and proximal femur is shown of a patient with cam-type femoroacetabular impingement. Impingement simulation in maximal flexion shows b) acetabular and c) femoral intra-articular impingement conflict (red circle, arrow).

Table III. Details of the collision detection software using 3D models of the hip. Reprinted with permission from Lerch et al.[29]

Software tool	Description/definition
Anterior pelvic plane was used as acetabular reference coordinate system	Defined by landmarks of both anterosuperior iliac spines and the pubic tubercles[15]
Femoral reference coordinate system	Defined by landmarks of the femoral head centre, the knee centre, and both femoral condyles[26]
Automatic rim detection[31]	For automatic detection of the osseous acetabular rim
Best-fitting sphere algorithm	For identification of the femoral head centre
Equidistant method	For virtual impingement-free hip motion analysis[32]
Distribution of the impingement zones	Calculated using a previously described clock face system[15,33]
Clockface coordinate system	Three o'clock was defined anteriorly for both right and left hips; the six o'clock position represents the acetabular notch
Intra-articular impingement	Intra-articular locations included the acetabular rim on the acetabular side and the femoral head and neck on the femoral side

(APP). The acetabular reference coordinate system was APP (Table III) using the landmarks of both anterosuperior iliac spines and the pubic tubercles.[15] The pelvis was evaluated in fixed position for the motion simulation, and the femur could move freely. For the femoral reference coordinate system, the centre of the femoral head, the knee centre, and both femoral condyles were used (Table III).[26] Using this CT-based 3D surface model (Figure 1), the calculated range of motion (ROM) and the individual impingement location were compared among the three groups.

Collision detection software. CT-based 3D models of 63 hips (37 patients and 26 controls) were evaluated using a validated 3D collision detection software for analysis of individual hip ROM and the acetabular and femoral impingement location.[15,32] Each hip joint underwent patient-specific dynamic impingement simulation with the help of previously validated software (HipMotion, University of Bern, Switzerland).[15] This software has been described previously,[19] and includes automatic detection of the acetabular rim,[31] a best-fitting sphere algorithm to identify the femoral head centre,[34] and the so-called equidistant method for motion analysis (Table III).[32] This method was designed for virtual 3D impingement simulation analysis.[32] Based on a previous validation study including soft-tissue (labrum, cartilage, and joint capsule), an impingement conflict could be detected with a mean accuracy of 2.6° (SD 2.5°).[32]

Using this impingement simulation, impingement-free maximal flexion was calculated for three groups. In a validation study of this software, intra- and interobserver measurements for flexion were good (intraclass correlation coefficient (ICC),[15] correlation coefficients ranging from 0.89 to 0.99).[35] A standardized and previously used system for location of impingement was used: three o'clock was consistently defined anteriorly; 12 o'clock

Table IV. Frequency of intra-articular and extra-articular hip impingement in different degrees of flexion (between 115° and 125° of flexion).

Intra-articular FAI	Cam FAI	Pincer FAI	Mixed FAI	p-value
115° flexion	33%	57%	67%*	0.012
120° flexion	50%	71%	83%*	0.011
125° flexion	78%	86%*	100%	NS
Extra-articular FAI	**Cam FAI**	**Pincer FAI**	**Mixed FAI**	**p-value**
115° flexion	0%	14%	0%	NS
120° flexion	6%	43%†	0%	p < 0.001
125° flexion	25%	57%†	33%	p < 0.001

Level of significance was adjusted for three groups (0.05/3 = 0.017) with the Bonferroni correction.
*Significant difference compared to cam-type FAI group.
†Significant difference compared to cam-type FAI group.
FAI, femoroacetabular impingement; NS, not significant.

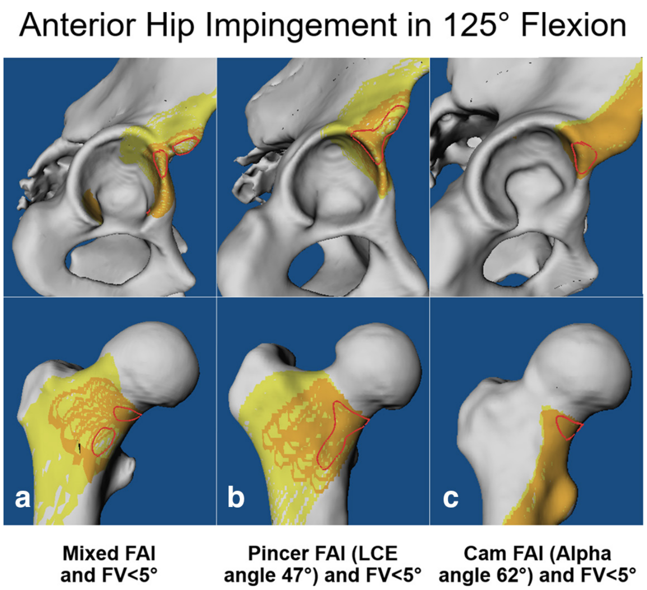

Fig. 2

Location of acetabular (top) and femoral (below) impingement for the three study groups (a) mixed-type femoroacetabular impingement (FAI), b) pincer-type FAI, and c) cam-type FAI) of patients with decreased femoral version (FV < 5°) is shown for 125° of flexion.

was defined superiorly; and six o'clock was defined inferiorly using the acetabular notch (acetabular side) and the femoral axis on the femoral side. In addition, the location of impingement was further specified as extra- or intra-articular. Intra-articular impingement locations were defined as described in Table III.

Statistical analysis. A sample size calculation and power analysis was performed for flexion in a fixed-effect one-way analysis of variance design with a level of significance of 5% and β error of 10%, given previously reported mean values for flexion of 125° in normal hips,[36] 105° in hips with FAI,[15] and a published mean SD of 13°.[36] This resulted in nine hips per group and in 18 hips with two groups.[37]

Statistical analysis was performed using Winstat software (R. Fitch Software, Germany). The data were tested for normal distribution with the Kolmogorov-Smirnov test. Since not all the parameters were normally distributed, non-parametric tests were used for comparison. To compare demographic and radiological data, ROM, or location of impingement among the three groups, a Kruskal-Wallis test was used; if significant, the Mann-Whitney U test was used to compare each of the combinations of two groups. To compare binominal demographic data and the prevalence of extra-articular impingement among the three groups, a chi-squared test was used; if significant, Fisher's exact test was used to compare among each of the combinations of two groups. The level of significance (p < 0.017) was adjusted for three groups (0.05/3 = 0.017) with the Bonferroni correction.

Results

Patients with pincer-type FAI (112° (SD 8°)) and patients with mixed-type FAI (110° (SD 8°)) had significantly (p < 0.001) decreased mean impingement-free flexion compared to control group (125° (SD 13°)). Patients with cam-type FAI had a mean impingement-free flexion of 117° (SD 8°).

The frequency of intra-articular impingement in 115° of flexion was significantly (p < 0.001) increased in hips with mixed-type FAI (67%) and hips with pincer-type FAI (57%), compared to hips with cam-type FAI (33%, Table IV).

Frequency of intra-articular impingement in 125° of flexion, 100% of the patients with mixed-type FAI, and 86% of the patients with pincer-type FAI (Figure 2) had a slightly increased frequency compared to 78% (Table IV) of the patients with cam-type FAI (Figure 3).

Patients with pincer-type FAI had a significantly (p < 0.001, chi-squared test) increased (57% (4 of 7 hips)) frequency of extra-articular subspine hip impingement conflict in 125° of flexion compared to control group (31% (8 of 26 hips)).

By contrast, 25% of the patients with cam-type FAI (4 of 16 hips, Table IV) and 33% of the patients with mixed-type FAI (2 of 6 hips, Table IV) had a similar frequency of extra-articular impingement in 125° of flexion.

Cam-deformity was not involved in maximal flexion (0% femoral one to three o'clock positions, Figure 4) of the patients. In maximal flexion, femoral impingement was

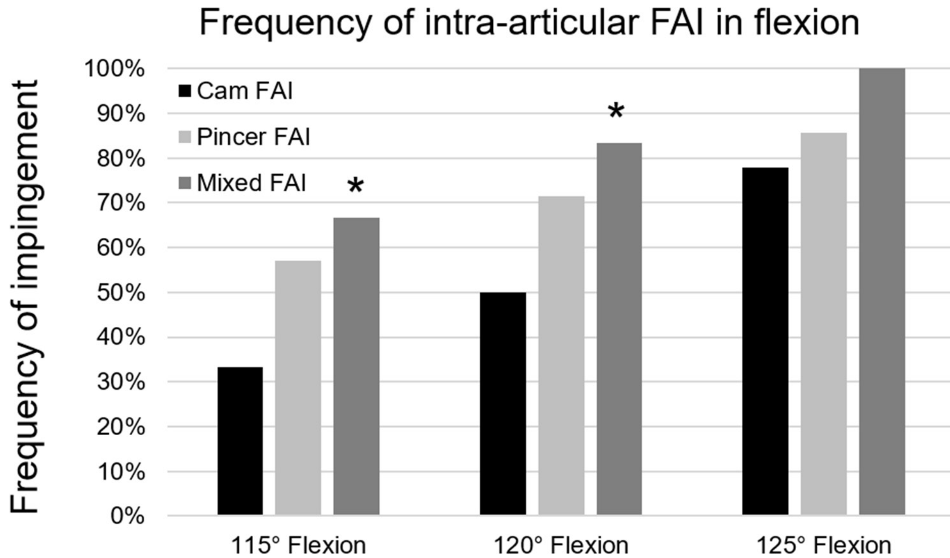

Fig. 3

Frequency of intra-articular hip impingement for 115°, 120°, and 125° of flexion is shown comparing three groups (mixed-type femoroacetabular impingement (FAI), pincer-type FAI, and cam-type FAI) of patients with decreased femoral version < 5°. The asterisk indicates significant difference compared to cam-type FAI.

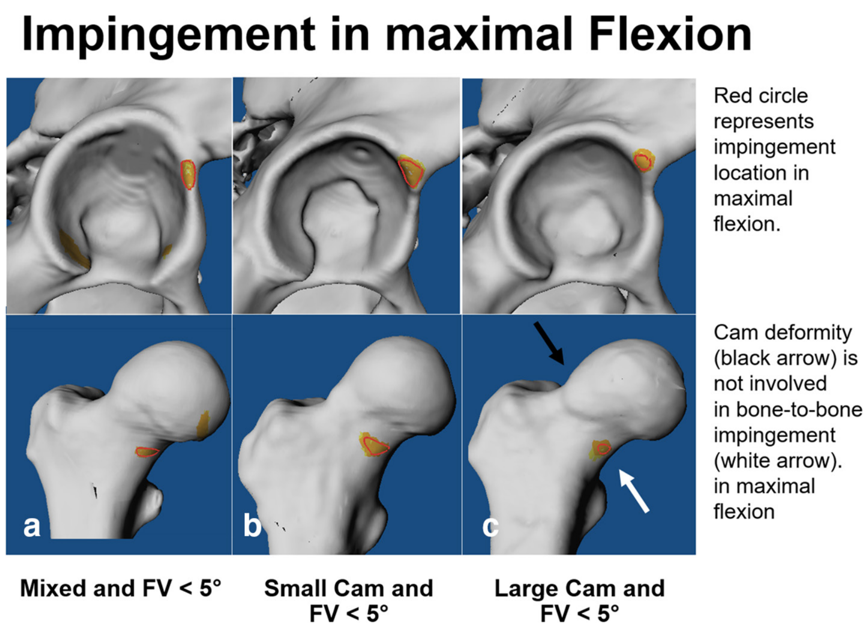

Fig. 4

Location of acetabular (top) and femoral (below) impingement in maximal flexion is shown for three patients with decreased femoral version (FV < 5°): a) a patient with mixed-type femoroacetabular impingement, b) a patient with a small cam deformity, and c) a patient with a large cam deformity.

mostly located anterior-inferior at four o'clock position (71% for pincer-type FAI (5 of 7 hips); 63% for cam-type FAI, (10 of 16 hips)) and five o'clock (37% for cam-type FAI (6 of 16 hips), Figure 5). Femoral impingement location in maximal flexion ranged from four o'clock position to five o'clock position for patients with pincer-type FAI, and from four o'clock position to six o'clock position for the other groups (Figure 5). Acetabular impingement was mostly located at two o'clock position for the patients with FAI (Figure 5).

Discussion

A retrospective study using patient-specific 3D models of the hip was performed to investigate impingement-free flexion and the location of impingement conflict in maximal flexion in FAI patients with decreased FV. This is important because exacerbation of hip pain in deep flexion is common in FAI patients. Impingement-free flexion was significantly ($p < 0.001$) lower in patients with pincer-type FAI compared to the control group. In addition, femoral impingement location in flexion was also

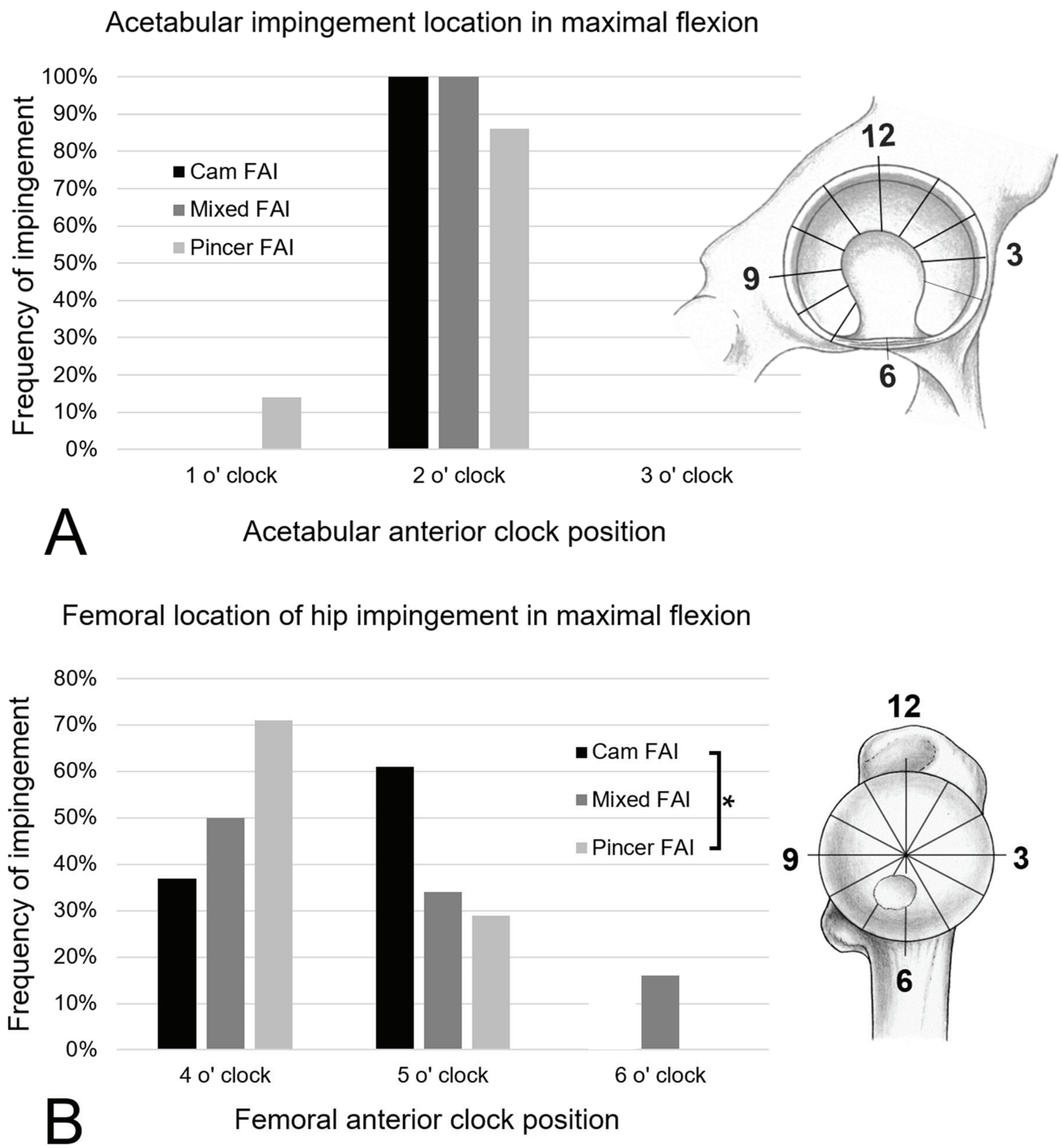

Fig. 5

Location of a) acetabular and b) femoral hip impingement in maximal flexion is shown for the three study groups. Clock face positions were used: 3 o'clock represents anterior, 12 o'clock represents superior, and 6 o'clock represents inferior. The asterisk indicates significant difference between cam-type and pincer-type femoroacetabular impingement (FAI).

located anterior-inferior, distal to the cam-deformity, for the patients with cam-type FAI combined with decreased FV. This could be important for the planning of osseous resection before hip arthroscopy. Frequency of extra-articular impingement conflict was higher in patients with pincer-type FAI compared to the control group and to patients with cam-type FAI. Interestingly, patients with mixed-type FAI had the lowest impingement-free flexion.

In terms of the amount of impingement-free maximal flexion, previous studies reported results that were both similar to and different from ours. Previous studies reported comparable values for flexion,[36,38] and a recent study of patients with increased FV found slightly higher flexion.[39] For 44 hockey players with symptomatic FAI, comparable values of flexion of 116° were described in 2015,[40] while a lower flexion of 107° (SD 12°) was described for ten patients with FAI in 2011 using a different software.[14] When comparing the flexion of 12 patients with cam-type FAI in a previous study (111° (SD 18°)),[15] slightly higher values (117° (SD 8°), Table IV) were found for the patients with cam-type FAI in the current study. When comparing maximal impingement-free flexion of the three patients (six hips) with mixed-type FAI (110° (SD 8°)) in the current study, a slightly higher flexion (117° (SD 14°)) was found for 22 hips with anterior FAI in a previous study.[36] Based on the validation study of the used software (with a mean accuracy of 2.6° (SD 2.5°)),[32] the difference found for flexion in the current study between the two subgroups of mixed-type FAI and pincer-type FAI of 2° lies within the software's variability. In a recent study evaluating 55 asymptomatic young adult women, maximum passive flexion of 101° was reported using ultrasound.[41] On the other hand, patients with subspine hip impingement (Type 2, mean flexion of 107°) exhibited similar values for flexion compared to the results for patients with mixed-type FAI (110° (SD 8°)) and pincer-type FAI (112° (SD 8°)) of the current study.[28]

The results for the acetabular location of hip impingement of patients with FAI are in line with the literature.[40,42,43] When analyzing femoral location of hip impingement in flexion, different locations have been reported in previous studies investigating impingement conflict. However, impingement was mainly evaluated using the flexion and internal rotation test (FADIR test, also called anterior impingement test).[43] Other studies reported mainly anterior-superior femoral impingement location to be between 1:00 and 1:45 clock position for 70 hockey players,[40] or between 12 o'clock (superior) and 3 o'clock (anterior) position for 40 FAI patients using the FADIR test.[43] This is in contrast to our results for anterior-inferior femoral impingement location (4 to 6 o'clock position, Figure 5b). In the current study, femoral impingement location was located anterior-inferior in maximal flexion for FAI patients with small and large cam deformities (Figure 4). Interestingly, the cam-deformity was not involved in hip impingement in maximal flexion. This is in accordance with a recent study which reported that midsagittal centre edge angle correlated with hip flexion, but cam-deformity did not.[11] The authors investigated 200 hips of FAI patients and analyzed the influence of radiological parameters for hip motion using multivariate linear regression analysis. They also reported that hip ROM can be influenced by acetabular and femoral pathomorphology. This is in accordance with the results of the current study that analyzed subgroups with different hip morphologies. The results of the current study are in line with another recent study of patients with cam or pincer morphologies, which evaluated hip impingement conflict in flexion using open MRI,[44] scanning hips in active squatting and passive sitting position. However, another study found that cam resection (femoral neck osteochondroplasty) improved postoperative flexion by 8° in a sitting posture,[45] analyzing a small sample size.

A considerable frequency of hip impingement was found for patients with cam-type FAI in 125° of flexion (Table IV). Anterior extra-articular subspine impingement (Figure 2) had a significantly ($p < 0.001$) higher prevalence (57%) in 125° of flexion in patients with pincer-type FAI compared to patients with cam-type FAI (22%, Table IV).

One strength of the current study is that the impingement simulation allows simulation of patient-specific osseous human hip motion. A previous validation study of this software for impingement simulation had an excellent ICC for ROM parameters,[15] especially for flexion (ICC > 0.88). This software allows simulation of maximal hip flexion, similar to deep flexion in squatting position. Previously, standing-to-sitting motion was evaluated using finite element analysis and showed increased peak contact pressure for a virtual hip joint with mixed-type FAI.[46] In contrast, the current study used patient-specific 3D models of the hip joint of symptomatic patients. This could be used directly in clinical practice for preoperative planning, considering the reduction of hip motion including the acetabular labrum and soft-tissue.[47] Therefore, clinical hip flexion could be even lower. Another strength of the study is that all patients were symptomatic (i.e. had anterior hip pain and documented positive anterior-impingement test/FADIR test) at the time of imaging. They also underwent standardized pelvic CT scans for evaluation of dynamic impingement simulation. Finally, patient-specific CT-based 3D models of all patients were evaluated, and validated software for ROM and impingement simulation via equidistant method was used.

This study also has clinical implications. Bony femoral impingement on the anterior-inferior (femoral 4 to 5 o'clock position) aspect of the femoral neck could be important for patients undergoing hip arthroscopy or open hip preservation surgery (surgical hip dislocation or anterior mini open approach).[48] Planning of cam resection or rim trimming before hip arthroscopy should be evaluated carefully in FAI patients with decreased FV who report hip pain in flexion, especially for patients with pincer-type FAI or mixed-type FAI (because of the low impingement-free flexion). Impingement simulation is based on patient-specific 3D models of the hip joint. The region of impingement should be known before hip arthroscopy surgery and open hip preservation surgery. This could help to better understand the biomechanical impingement conflict in flexion. In the authors' opinion, bone resection on the anterior-inferior (femoral 4 to 5 o'clock position) aspect of the proximal femur is not a clinical option for surgery because of the risk of iatrogenic femoral neck fracture. To treat patients with hip pain in flexion, acetabular rim trimming can be performed safely and seems, in the authors' opinion, to be the treatment of choice. To define optimal treatment for these patients, further studies are needed to simulate bone resection.

In a previous systematic review,[49] residual deformity or under-correction were risk factors for inferior patient-related clinical outcomes after hip arthroscopy in patients with FAI, and these were the most common causes for revision hip arthroscopy for FAI treatment.[49,50] Theoretically, to treat a patient with hip pain in flexion and extra-articular subspine impingement, a subspine decompression and/or acetabular rim trimming could be performed, in addition to cam resection. Based on the current study, routine assessment of hip pain in deep flexion or squatting to identify patients with hip impingement in flexion could be relevant for FAI patients with decreased FV. In the case of hip pain during sitting or limited sitting tolerance, deep flexion should probably be avoided.

Additionally, this study has implications for daily activities (e.g. putting on shoes), sex, and sports (e.g. squats). Adaptation of daily activities, sports, and physical therapy should be evaluated in FAI patients, especially for patients with mixed-type and pincer-type FAI and femoral retroversion reporting hip pain in flexion. Exercises with deep flexion, such as split squat (also called lunges) or squats could exacerbate hip pain in flexion. In addition, sports with maximal flexion (e.g. ballet dancing, karate kicks, or yoga) could be at risk for hip impingement. For ballet, extreme hip motion and hip impingement have been reported previously in a motion capture study, describing certain positions that required more than 120° of flexion.[51] This is in accordance with a recent systematic review which summarized that supraphysiological hip motion is required for many activities.[52] The review summarized the amount of flexion necessary for daily activities such as shoelace-tying (121°), squatting (121°), and lying down (130°).[52] It seems probable that patients with pincer-type and mixed-type FAI, and femoral retroversion, have difficulties during these daily activities due to limited flexion of 112° or 110° (Table IV).

This study also has limitations: first, although the software used for impingement simulation is based on bone segmentation and calculates the osseous ROM, it was impossible to take into account soft-tissue such as acetabular labrum,[47] muscles, cartilage, ligaments,[53] or the pulvinar in the acetabular fossa.[54] This prevents direct comparison to motion capture studies.[52] This is unavoidable when using pelvic CT scans, but could be done in the future using MRI of the hip.[55–57] However, this is also the case for published ROM results using different collision detection software.[14,58] Patients with severe hip deformities, including patients with high FV[39] and hips with post-Perthes' deformities,[33] were investigated with this method. Using the equidistant method allowed the application of this software to patients with various hip deformities. Second, the patients were recruited from a university hospital, which means that there could be a potential selection bias of complex patients with limited generalizability. Third, no report on clinical follow-up was performed. In addition, the number of patients in the subgroups is small; some subgroups had a lower sample size as calculated in the sample size calculation, which limits the generalizability of the results. Patients evaluated for hip preservation surgery are usually younger than patients with THA, which prevents comparison to patients undergoing CT-based navigated THA. Fourth, previous studies reported the hip motion needed for certain positions or combined movements (e.g. combined flexion and internal rotation) instead of the maximum impingement-free hip ROM in one direction.[52] Last, the effect of pelvic incidence, pelvic tilting,[59,60] and tibial torsion was not analyzed. Posterior pelvic tilting could be performed to avoid anterior hip impingement; a recent dual fluoroscopy study has reported that FAI patients have 5° less anterior pelvic tilt.[59]

In conclusion, bony femoral impingement conflict in flexion was located anterior-inferior distal to the cam-deformity. This differs from previous studies that reported anterior-superior femoral impingement location during the anterior-impingement test. This could be important for patient counselling (counselling interview) because exacerbation of hip pain in deep flexion is common in FAI patients. Hip impingement in flexion has implications for daily activities (e.g. putting on shoes), sex, and sports (e.g. squats). This could be important for preoperative planning and bone resection (cam resection or acetabular rim trimming) during hip arthroscopy or open hip preservation surgery to ensure that the region of bony impingement is known before surgery.

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