Original Article

Arthroscopic Femoral and Acetabular Osteoplasties Alter the In Vivo Hip Kinematics of Patients With Femoroacetabular Impingement

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Purpose: Three-dimensional (3D)−two-dimensional (2D) fluoroscopic image registration was used to measure 3D hip kinematics before and after hip arthroscopy in patients with femoroacetabular impingement (FAI). **Methods:** In total, 24 subjects diagnosed with FAI (21 unilateral, 3 bilateral) were prospectively recruited. A clinical impingement test was performed on both hips while the patient was awake and then while anaesthetized, and in the operative hip after arthroscopic osteoplasties and labral repair. Fluoroscopy was used to image the hip during the impingement tests. Images were analyzed using 3D-2D image registration to calculate joint kinematics. The examiner's hand was instrumented with a glove to measure internal rotation torque applied to the hip during each test. **Results:** Internal rotation increased by 3.7° (standard error [SE] 0.95°) after surgery ($P = .001$). Maximum displacement of the femoral head out of the acetabulum was 4.0 mm (SE 0.5 mm) in the operative group before surgery and 1.8 mm (SE 0.3 mm) after surgery ($P < .001$). This was due to a decrease in lateral displacement by 1.3 mm (SE 0.4 mm, $P = .002$) and proximal displacement by 0.8 mm (SE 0.3 mm, $P = .013$). Internal rotation torque was greater in the operative hips when anaesthetized compared with when awake, by 5 Nm (SE 1.2 Nm, $P < .001$), and greater in the contralateral hips than the operative hips when awake by 8.4 Nm (SE 1.4 mm, $P < .001$). **Conclusions:** Arthroscopic osteoplasty and labral repair increased hip range of motion and reduced femoral head displacement from the acetabulum during the IR90 provocation test (i.e., hip flexion to 90°, maximum internal rotation) in patients with FAI. This suggests that the impinging acetabular rim acted as a fulcrum before surgery and may have caused edge loading that was reduced after surgery. **Level of Evidence:** Level IV case series, therapeutic study.

Femoroacetabular impingement (FAI) involves the abnormal abutment of the femoral neck on the acetabulum, causing significant pain and functional

limitations and also may predispose to hip osteoarthritis.[1-3] Underlying anatomical abnormalities causing impingement include femoral "cam"-type lesions and acetabular "pincer"-type lesions. Cam lesions occur most often in young male patients and result in shear injury to the labrum, which may progress to chondral injury and labral detachment.[2] Pincer lesions are more common in female patients and result in labral damage secondary to repetitive abutment at the femoral head−neck junction.[4] Arthroscopic surgery increasingly is being performed to address both of these anatomical abnormalities[5] with a goal of restoring normal, impingement-free, hip kinematics.

Our current understanding of the kinematics of FAI, before and after arthroscopic surgery, is limited by a number of factors. First, the very existence of impingement and its exact location is only inferred from a compilation of history, physical examination, static imaging, and image-based simulations.[6-11] Before surgery, the impingement event is not actually

observed radiographically; hence, the specific impingement location can only be estimated and little is known of events subsequent to impingement, such as "levering out" of the femoral head on the acetabular rim. Second, intraoperative arthroscopic methods used to assess the adequacy of bone resection only assess changes in bony morphology and are more limited in assessing dynamic changes, such as in hip range of motion.[12,13] Consequently, a surgeon may remove too little bone, resulting in residual impingement, or excessive bone, which increases the risk of either fracture on the femoral side or dislocation on the acetabular side.[14,15] Therefore, a method that accurately characterizes hip kinematics before and after surgery for FAI may help surgeons further understand this pathology and assist in more effective surgical planning and evaluation, leading to better postoperative outcomes.

In the current study, a validated method involving intraoperative 3-dimensional (3D)−2-dimensional (2D) image registration was used to address the aforementioned limitations.[16-18] The method was implemented to measure 3D kinematics before and after hip arthroscopy in patients with FAI.

The study addressed the following 2 null hypotheses: (1) No differences would exist in rotation or translation of the hip joint during a clinical impingement test between hips with FAI before and after arthroscopic osteoplasty and labral repair. (2) No differences would exist in rotation or translation of the hip joint during a clinical impingement test between hips with FAI and contralateral asymptomatic hips.

Methods

Ethics approval for this study was obtained from the local ethics review board (ETH 6.15.108).

In total, 24 patients diagnosed with either unilateral or bilateral FAI, based on clinical and radiographic measures, were prospectively recruited to the study. Exclusion criteria included pregnancy, age <18 years, and previous hip surgery. Each subject completed preoperative the 33-item International Hip Outcome Tool (iHOT-33) and Hip Disability and Osteoarthritis Outcome Score (HOOS) questionnaires for their symptomatic hips and repeated iHOT-33 at 6 weeks' postoperation. Those patient with unilateral FAI also completed the first 2 domains of the HOOS (symptoms and pain), focusing on their asymptomatic hip. Lateral center edge angle was measured from anteroposterior pelvic radiographs for both operative and contralateral sides, and both pre- and postoperatively from computed tomography (CT) scans.[19] Alpha angles were measured from digitized points on radially reconstructed CT scans of the femoral neck at 12-o'clock, 1:30-o'clock, and 3-o'clock positions. Femoral version was calculated

Fig 1. Clinical impingement test* performed on an anaesthetized patient before arthroscopic surgery demonstrating an instrumented glove to measure torque applied to the hip, and positioning of the image intensifier to view the side profile of the acetabular rim. *Internal rotation in 90° of hip flexion.

by overlaying the axis of the femoral neck onto the transepicondular axis of the knee in the axial plane.[20]

A clinical impingement provocation test (hip flexion to 90°, maximum internal rotation [IR90]) was performed on both hips of each subject just before surgery and sedation, with the patient lying supine on a hospital bed. The patient was instructed to flex their hip such that their femur was vertical, which was confirmed visually by the examiner, and a spirit level was then used on the lateral femur to check neutral add/abduction and on the tibia to check that the anterior border was parallel to the floor. The examiner's hand was instrumented with a glove (Fig 1) containing a uniaxial force transducer (FC 22 piezoresistive compression load cell, 0-50 lbs, Measurement Specialties, Fremont, CA; accuracy 1% full scale deflection). A 10-bit analog to digital card (Phidgets 8/8/8 interface kit; Phidgets, Calgary, Canada) using Matlab (R2015b; MathWorks, Natick, MA) on a laptop computer (Dell Inspiron 15 5000; Dell, Round Rock, TX) was used to record the laterally directed force applied to the distal tibia. A custom cylindrical plastic case with a circular metal base was attached via Velcro straps approximately 5 cm proximal to the medial malleolus. The plastic case acted as a receptacle for the force transducer, with a clearance of 2 mm on each side between the side of the transducer and the receptacle. The plastic case had a convex base that enabled only the contact element of the force transducer to touch the plastic base when the leg was loaded. The distance between the plastic case and the knee joint line was measured with a measuring tape. The examiner's contralateral hand was used to stabilize the knee by holding under the calf as close to the knee

as possible. An estimate of internal rotation torque was calculated as follows:

$$\text{internal rotation torque} = \text{distance between the plastic case and the knee joint line} \\ \times \text{laterally directed force applied to the distal tibia}$$

During the clinical impingement test, each subject used a handheld switch that they pressed when they started to experience pain. If they pressed the switch, the test was positive. The switch signal was synchronized with the signal from the force transducer.

After the patient was anaesthetized, the same clinical impingement test was performed, with the patient supine on the operating table (Fig 1). Torque applied to the hip was measured in the same manner. An image intensifier (II) (Fluorostar; GE Healthcare, Chicago, IL) was positioned such that the acetabular rim was viewed parallel to its edge, so that it captured impingement occurring at the most superior aspect of the visible acetabular rim. This involved positioning the axis between the emitter and receiver at approximately 45° to the sagittal plane, then tilting the II about this axis by an amount equal to the anteversion of the acetabulum measured from DYONICS PLAN simulation software (Smith & Nephew, London, UK), aiming for the anterior and posterior walls to align as closely as possible, and for the walls to appear vertical on the II screen. The II was then rotated about an axis perpendicular to the acetabular rim edge, by approximately 30° from vertical such that the most superior region of the acetabular rim that was visible in the II image corresponded to the 1-o'clock position of acetabular rim impingement (Fig 1).

During the clinical impingement test, approximately 10 static images were taken while incrementally increasing the amount of internal rotation of the hip, until impingement was seen on the images visible on the II screen, and/or the examiner (T.W.) felt significantly increased resistance to further rotation. This test was repeated on the contralateral side.

After arthroscopic femoral and acetabular osteoplasties and labral repair, which were performed by a single surgeon, the test was repeated on the operative side. The extent of the femoral and acetabular osteoplasties was planned using the DYONICS PLAN software (Smith & Nephew) and was confirmed intraoperatively on anterior/posterior image intensifier images, and on modified Dunn views.

The investigators did not influence the muscle relaxant protocol used by the anesthetist, who followed their usual clinical practice. In most cases, no muscle relaxant was used, except if required by the surgeon intraoperatively.

The locations of pincer lesion resection, labral damage, and femoral osteoplasty were recorded postoperatively by the surgeon, using clockface terminology, where the most superior aspect of the acetabular rim and femoral neck corresponded to 12 o'clock (0°), and the most anterior aspect corresponded to 3 o'clock (90°).

Images collected intraoperatively were analyzed using "Orthoviz," a 3D-2D image registration program, with validated accuracy of approximately 1 mm of translation and 1 degree of rotation. Details of the method have been described previously.[16,18] Joint kinematics were measured using the International Society of Biomechanics recommendations for hip joint kinematics.[21] Each patient's preoperative planning CT scan (Aquilion Prime; Toshiba, Tokyo, Japan; 2-mm slice thickness, 0.95 mm/pixel resolution) was used to define a 3D model of the hip joint. In particular, flexion, abduction and internal rotation at terminal motion, and the maximum total displacement of the femoral head out the acetabulum, along with lateral, proximal, and anterior displacement components, were measured for each clinical test. The position of impingement during the activity was estimated using angular clockface terminology for both the femoral neck and acetabular rim, with 12 o'clock corresponding to the superior rim (0°) and 3 o'clock corresponding to the anterior rim (90°).

The experimental protocol was tested on 2 subjects before implementation. During this pilot testing, 2 impingement activities were assessed: flexion/adduction/internal rotation and IR90. During the flexion/adduction/internal rotation test, investigators were concerned that postoperative thigh swelling may have limited the terminal motion of the activity, risking the scenario that soft-tissue impingement between thigh and abdomen limited motion, rather than hip joint impingement. To avoid this, IR90 test was chosen, which had the added benefit of enabling 2 of the 3 degrees of freedom of hip rotation, hip flexion and abduction, to be controlled.

Statistical analysis was performed in SPSS (version 23, IBM Corp., Armonk, NY) and Microsoft Excel (Microsoft Office 2013, Seattle, WA). Preoperative and postoperative iHOT-33 scores were compared with paired Student t tests. Radiographic parameters (lateral center edge angle and alpha angles) were compared between operative and contralateral hips

Table 1. Demographics of the Study Cohort (N = 22, 45% Male, 55% Female)

Demographics	Mean	SD
Age, y	34.1	13.2
Height, cm	174.5	8.5
Weight, k.g	74.3	13.9
BMI	24.3	3.2

BMI, body mass index; SD, standard deviation.

with paired Student t tests. Torque and kinematic measurements (angles and displacements) were compared using a linear mixed model, with side (operative or contralateral) and time (preoperative, postoperative) nested within operative side as fixed factors and subject as a random factor. A Bonferroni correction was applied to account for 6 repeated kinematic measures (significance level of <.008 required for $\alpha = 0.05$). Power calculations were based on an expected clinically significant difference in internal rotation between groups of 10°, with a standard deviation of 15.3 degrees (1) ($\alpha = 0.05$, 80% power). This indicated that a minimum of 21 subjects were required for the study.

Results

Two subjects were excluded from the study: one subject was excluded because they were subsequently found to have had previous hip surgery, and the other subject was excluded because no data were recorded. Demographic data for the 22 subjects who underwent testing are described in Table 1. There were 10 male patients, 12 female patients, 3 patients with bilateral FAI, and 19 patients with unilateral FAI, which comprised 11 left and 8 right hips.

Mean IHOT 33 scores improved by 9.2 (standard error [SE] 3.8) from 40.6 to 49.8 at 6 weeks after operation ($P = .03$). The preoperative scores for the first 2 domains of HOOS in symptomatic and contralateral sides were 49.9 (SE 3.0) and 97.1 (SE 0.9) ($P < .001$), respectively.

No significant differences in radiographic parameters (lateral center edge angle or alpha angles) were observed between the operative and nonoperative

(contralateral) sides ($P > .1$). These measurements were not obtained for the nonoperative sides in 2 patients as contralateral images were not available. After surgery, the lateral center edge angle reduced by 4.7° (standard deviation [SD] 3.2°), and the alpha angle reduced by 5.3° (SD 8.4°), 12.3° (SD 11.4°), and 15.7° (SD 12.8°) at 12-o'clock, 1:30-o'clock, and 3-o'clock positions, respectively (Table 2) ($P < .01$). Femoral version in the operative hips was 9.5° of anteversion (SD 8.2°) and 9.5° in the nonoperative hips (SD 6.4°).

The clinical impingement test, performed when the patient was awake, was positive in all 25 preoperative hips but in only 2 of 19 contralateral hips. Mean torque applied to the hip was greater in the operative hips when anaesthetized compared with when awake, by 5 Nm (SE 1.2 Nm) ($P < .001$), and greater in the contralateral hips than the operative hips when awake by 8.4 Nm (SE 1.4 Nm) ($P < .001$) (Fig 2). In total, 10% of torque measurements were missing due to recording errors. No significant differences in applied torque existed between the anaesthetized preoperative, postoperative, or contralateral groups.

The surgeon's mean estimated arc of resection of the femoral cam lesion ranged from 10.4° (SE 5.4°) to 98.4° (SE 5.5°) and for the pincer lesion from 11.9° (SE 4.8°) to 80.6 (SE 3.2°). From the measured 3D kinematics, the mean estimated location of impingement was 64.1° (SE 6.8°) on the femoral neck and 16° (SE 3.2°) on the acetabular rim.

Average internal rotation significantly increased after surgery by 3.7° (SE 0.95°) in the symptomatic hips (Fig 3) ($P = .001$). In total, 18 of 25 postoperative hips demonstrated increased internal rotation. There were no significant differences in internal rotation between preoperative and contralateral hips. Adduction was reduced in contralateral hips compared with pre- and postoperative hips, but the difference was not statistically significant (Fig 3). Average flexion was greater in pre- and postoperative hips compared with contralateral hips but this was not statistically significant (Fig 3).

Average maximum total displacement of the femoral head out of the acetabulum was 4.0 mm (SE 0.5 mm) in the operative hip before surgery and 1.8 mm (SE 0.3 mm) after surgery ($P < .001$) (Fig 4). This was due to a decrease

Table 2. Mean (SD) Morphologic Measurements From Plain Radiograph and CT Scans of the Symptomatic and Nonsymptomatic (Contralateral) Hips Measured Before Surgery

	Preoperative N = 22	Postoperative N = 22	Mean Difference (N = 22) 95% CI	P Value
Lateral center edge angle	36.5 (3.9)	31.7 (4.3)	−4.7 (−6.1 to −3.4)	<.001
Alpha angle, 12:00	68.9 (6.4)	63.6 (9.3)	−5.3 (−8.8 to −1.8)	.007
Alpha angle, 1:30	73.3 (11.6)	60.9 (9.3)	−12.4 (−17.1 to −7.6)	<.001
Alpha angle, 3:00	70.9 (11.6)	55.3 (10.3)	−15.7 (−21.1 to −10.3)	<.001

NOTE. Alpha angles are described according to clock face terminology, where 12:00 o'clock is the most superior point on the radially reconstructed CT scans of the femoral neck.

CI, confidence interval; CT, computed tomography; SD, standard deviation.
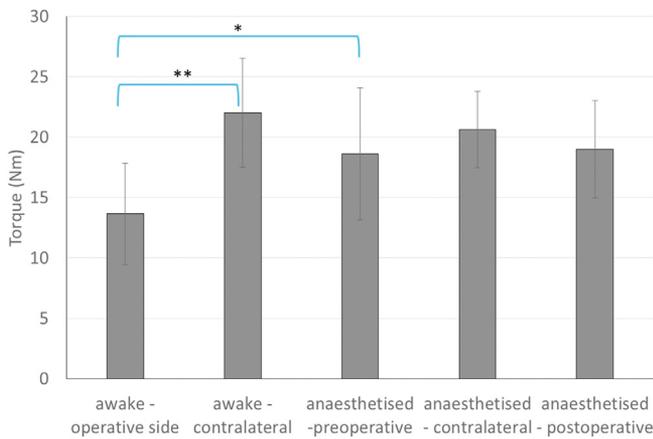
Fig 2. Torque (Nm) (±1 standard deviation) applied during the impingement test measured on both operative and contralateral sides while subjects were awake, and anaesthetized pre- and postoperatively. Increased torque ($P < .001$) was applied to awake contralateral hips** and to anaesthetized preoperative hips* compared with preoperative hips in awake patients.

in lateral displacement by 1.3 mm (SE 0.4 mm, $P = .002$) and proximal displacement by 0.8 mm (SE 0.3 mm, $P = .013$) after surgery. Lateral and proximal displacements were significantly lower in the contralateral group than in the preoperative group by −2.2 mm (SE 0.6 mm, $P = .001$) and −1.8 mm (SE 0.6, $P = .003$), respectively, although no significant difference in total displacement was observed. There were no differences in anterior displacement between groups.

Discussion

In patients with FAI being treated with arthroscopic osteoplasties and labral repair, significant differences in hip joint kinematics were found between preoperative and postoperative hips and between preoperative and asymptomatic contralateral hips, leading to rejection of the study's null hypotheses. Internal rotation during the impingement test increased after arthroscopic surgery in the FAI hips, a finding that has been demonstrated in simulation studies but not before in vivo.[1,9] Studies of normal gait, squatting, and stair-climbing also have demonstrated differences in range of motion of the hip and pelvis in FAI compared with patients without FAI and also between pre- and postoperative hips.[9,22-26] However, these studies used external skin markers, which are prone to much greater errors than 3D-2D image registration. A rigorous study using biplanar fluoroscopy and image registration by Kapron et al.[23] demonstrated a trend toward reduced range of motion in an FAI group compared with a control group, but small subject numbers limited their statistical analysis. Recent studies by Hansen et al.[27,28] using 3D in vivo dynamic roentgen stereophotogrammetric

analysis demonstrated no significant differences between preoperative and postoperative kinematics at 1 year. Nevertheless, increased internal rotation before and after surgery in the current study demonstrated that the surgical procedures performed on these patients successfully increased their range of internal rotation, by 3.7°, which is not clinically significant.[29]

Displacement of the femoral head out of the acetabulum was greater in the preoperative hips compared with postoperative and contralateral hips, which suggests the impinging acetabular rim acted as a fulcrum before surgery. This was most significant in lateral and proximal displacement directions, which corresponded to the femoral head "levering out" of the acetabulum with an average impingement location near 12 o'clock, which is close to the average acetabular impingement location measured to be 16°. This finding suggests that levering of the femoral head out of the acetabulum occurred in symptomatic patients with FAI but was reduced postoperatively by resecting the impinging bone, and was less significant in contralateral hips. Hansen et al.[27,28] did not find such levering before and after surgery, but their clinical tests were on awake patients, so the torques applied may have been less, as demonstrated in the current study. Levering of the femoral head may suggest significant edge loading at the impingement zone, and may be responsible for accelerated cartilage and labral damage.[30] If osteoplasty and labral repair reduce this levering and the resultant edge loading, it strengthens the argument that surgical intervention may reduce the onset of osteoarthritis in the longer term.

Levering of the femoral head during impingement may introduce unforeseen loading mechanisms, in addition to edge loading at the acetabular rim, which
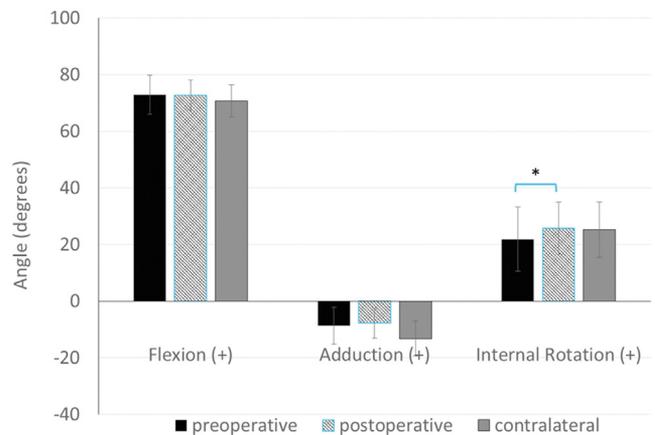
Fig 3. Hip joint angles (±1 standard deviation) during terminal motion of the impingement test, measured in the operative hip (preoperative and postoperative) and in the contralateral hip. Internal rotation increased in operative hips after surgery* ($P = .001$).
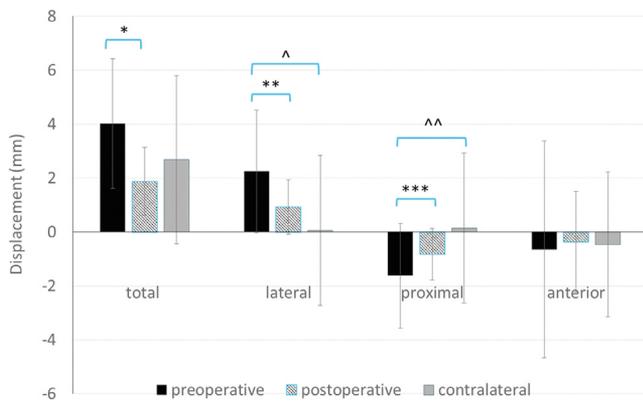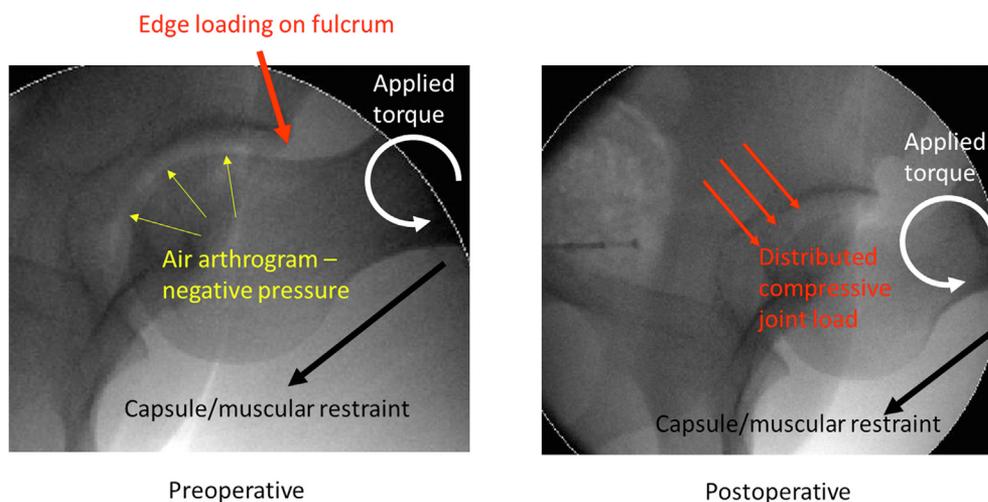
Fig 4. Femoral head displacements (± 1 standard deviation) during terminal motion of the impingement test, measured in the operative hip (preoperative and postoperative) and in the contralateral hip. Total displacement significantly decreased after surgery in operative hips* ($P < .001$), which was due to decreases in lateral** ($P = .002$) and proximal*** ($P = .013$) displacement components. Lateral^ and proximal^^ displacements were reduced in contralateral hips compared to preoperative hips ($P = .001$ and $.003$, respectively).

subchondral bone, providing a complementary destructive force to the shearing at the periphery due to edge loading.[31] Furthermore, it is unclear if, as intra-articular gas is resorbed, cavitation occurs as the gas bubbles implode,[32,33] causing localized regions of extreme pressure which are known in other engineering applications to cause significant surface damage, although the impact of cavitation in human joints is controversial.[34,35] Postoperatively, after resecting the impinging bone, it is likely this edge loading was reduced with the external torque being balanced by a greater contribution from muscle and capsular tensile forces and intra-articular compressive forces (Fig 5), which joints surfaces are structured to withstand.

A number of features of the current study reduced confounding factors. First, patients were tested while anaesthetized, which enabled similar torques to be applied to the operative and contralateral hips, before and after surgery. The torque applied to the symptomatic hip was less when each patient was tested awake, due to pain. Therefore, awake comparisons between symptomatic and asymptomatic hips are likely to be confounded by differences in applied torque. Second, the predicted location of impingement on the acetabular rim and femoral neck during IR90 was within the range of osteoplasty boundaries recorded by the surgeon, which suggests the IR90 activity successfully targeted the impinging region that was resected by the surgeon. Furthermore, the changes between preoperative and postoperative measurements of alpha and lateral center edge angles quantify the femoral and acetabular osteoplasties performed.

Finally, the main conclusion of the study was that arthroscopic osteoplasty and labral repair increased hip range of motion and reduced femoral head displacement from the acetabulum during the IR90 provocation test in patients with FAI. This suggests that the

may precipitate further acceleration of cartilage degeneration. These proposed mechanisms are demonstrated in free body diagrams representing the forces applied to the hip before and after surgery (Fig 5). An applied external torque to the hip is ideally balanced by a combination of forces applied by the hip capsule and surrounding musculature, along with intra-articular compressive forces. In a preoperative FAI hip, as the neck impinges on the acetabular rim and the head levers on the acetabulum, a significant negative pressure may be created inside the hip joint, which may result in formation of gaseous bubbles, evident as an air arthrogram (Fig 5).[11] This "suction" force may contribute to articular cartilage delaminating from

Preoperative

Postoperative

Fig 5. In preoperative FAI hips during the impingement test with an externally applied internal rotation torque, equilibrium is maintained via capsule/muscle restraint forces, loading at the fulcrum on the edge of the acetabulum and likely negative intra-articular pressure. If edge loading is eliminated by arthroscopic surgery, postoperative equilibrium is maintained by capsule/muscle forces and intra-articular compression.

impinging acetabular rim acted as a fulcrum before surgery and may have caused edge loading that was reduced after surgery. Despite the significant kinematic differences between preoperative FAI and contralateral asymptomatic hips, no significant differences were observed in static radiographic parameters (lateral center edge, alpha angles) despite the contralateral hips having negative impingement tests in 17 of 19 patients. This finding of incidental positive FAI radiographic parameters in asymptomatic subjects has been well documented.[36,37] It is possible that both hips in these subjects were predisposed to FAI due to their bony morphology, but injury had only occurred on the symptomatic side. Given there were no obvious differences in bony anatomy detected on radiographic measures, it is likely that soft-tissue irregularities, such as an entrapped labrum,[13] were sufficient to restrict internal rotation and cause edge loading, but were too subtle to be detected on standard radiographic measurements for FAI. This reinforces the premise of this study that since FAI is a dynamic event, dynamic imaging tests are likely to provide greater understanding of the pathology.

Limitations

The results of this study should be interpreted in view of its limitations. The use of the proposed method for diagnosis of FAI in awake patients is limited because of the uncontrolled effect of pain on range of motion. Furthermore, the location of impingement on the acetabulum and femoral neck were estimated based on extrapolating the trajectory of joint motion until bony collision occurred. Precise contact location or pattern of impingement could not be determined because the dimensions of the femoral cartilage and acetabular labrum were not accurately defined by the preoperative CTs.

Conclusions

This study provided evidence that arthroscopic osteoplasty and labral repair in patients with FAI increased hip range of motion and reduced levering of the femoral head from the acetabulum during the IR90 provocation test. This suggests the impinging acetabular rim acted as a fulcrum before surgery, which may have caused significant edge loading, which likely reduced after surgery.

Acknowledgments

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