Femoroacetabular impingement (FAI) occurs when the head or neck of the femur abuts against the rim of the acetabulum. The principles of hip impingement are studied with regard to total hip arthroplasty, in which components must be designed to minimize wear and dislocation.\(^1\)\(^-\)\(^3\) Impingement is also studied in congenital hip dysplasia and pediatric hip disorders, where dysmorphic native anatomy or surgically altered anatomy provides a readily identifiable source of impingement.\(^4\)\(^-\)\(^7\)

The recognition of hip impingement in these patient populations has led several authors to examine FAI as a potential cause of early, idiopathic osteoarthritis (OA) in younger patients. The work of Ganz et al is particularly instrumental in defining FAI, as this group has performed surgical dislocation of the hip in several hundred patients with symptomatic impingement and has meticulously documented their intraoperative observations.\(^8\)\(^-\)\(^10\) These observations provide the basis for 2 proposed mechanisms of FAI: an abnormally shaped (nonspherical) or excessively large femoral head or neck, or overcoverage of the proximal femur by the acetabulum.

Although these anatomic features can be easily recognized by the use of readily available imaging techniques, such as plain radiographs, in vivo characterization of abnormal contact between the femur and the acetabulum proves more difficult. Devising and implementing appropriate surgical interventions, therefore, is also difficult. In this review we aim to summarize the proposed biomechanical mechanisms of FAI, the analytical methods currently available to study FAI biomechanics, and the topics that future biomechanical studies of FAI will need to address.

**Proposed Mechanisms of FAI**

Ganz et al\(^9\) proposed FAI as a mechanism for the development of early OA in the absence of dysplasia after performing surgical dislocation of the hip on more than 600 symptomatic patients. On the basis of the location of labral and articular cartilage pathology, the authors suggested that FAI occurred most often in terminal flexion and that additional shearing damage could occur if terminal flexion was accompanied by rotation. Furthermore, the authors suggested that the impingement could result from 2 possible morphologic abnormalities, the cam lesion and the pincer lesion.
Defining the Normal Hip

In describing biomechanical abnormalities, it is important to understand the criteria by which normal hip morphology is generally described, which is drawn largely from the study of hip dysplasia. Because it best identifies labral and cartilage pathology, magnetic resonance arthrography is the gold standard in clinical imaging. However, the following measures focus on the bony abnormalities presumed to cause FAI.

The center-edge angle (CEA) was developed to quantify hip dysplasia in which the acetabulum is too shallow, thus predisposing patients to instability of the hip joint. The CEA is measured on an anteroposterior (AP) radiograph of the hip as the angle between a vertical line that intersects the center of the femoral head and a line that is drawn from the center of the femoral head to the lateral-most aspect of the acetabulum (Fig. 1A). A value >20° is generally accepted to indicate a nondysplastic hip. An AP radiograph of the hip can also be used to evaluate for the presence of a crossover sign, which denotes acetabular retroversion when the anterior rim of the acetabulum (which should be medial) runs more laterally in the most proximal part of the acetabulum and crosses the posterior rim distally.

The advent of magnetic resonance imaging (MRI) has allowed for more comprehensive evaluation of femoral head and neck morphology. The head of the femur is generally accepted to be shaped as a sphere that narrows to form the femoral neck. This narrowing provides an offset between the radius of the femoral head and that of the femoral neck, which allows a greater range of motion about the hip (Fig. 2A, 2B). The alpha angle is proposed to evaluate deviations in the sphericity of the femoral head and the normal offset between the femoral head and the femoral neck. The alpha angle is measured between a line parallel to the axis of the femoral neck and a line drawn from the center of the femoral head to the point at which the distance from the center of the femoral head to the cortex of the femoral head or neck first exceeds the radius of a circle fit to the femoral head (Fig. 1B). Although the values that indicate pathology are debated, values <50° are generally accepted to represent normal proximal femur morphology.

Gosvig et al also recently proposed the triangular index for evaluation of proximal femoral morphology. The triangular index is calculated by first fitting a circle to the femoral head and measuring the radius of the circle (r). The next line is drawn along the longitudinal axis of the femoral neck, and then another line is drawn perpendicularly to this line at a distance of r/2 from the center of the femoral head. Finally, a triangle is drawn with a hypotenuse (R) going from the center of the femoral head to the point at which the lateral cortex of the femur intersects the line previously drawn perpendicularly to the longitudinal axis of the femur (Fig. 1C). When a radiograph with 1.2 times magnification is used, the proximal femur is classified as abnormal when R ≥ r + 2 mm. This method has the advantage of requiring only an AP radio-

![Figure 1](image_url)
Cam Lesion

A cam is a rotating or sliding piece in a mechanical linkage that translates rotary motion into linear motion or vice versa. This translation is generally caused by the rotation of an eccentrically shaped wheel, sphere, or cylinder. The femoral head is normally spherical and thus produces purely rotational movements. However, an abnormality in the shape of the femoral head or neck can disrupt these purely rotational movements to produce impingement or linear movement, hence the term “cam lesion.” Some authors have also used the term “pistol grip deformity” when describing this lesion because of the resulting appearance of the proximal femur on an AP radiograph.

The proposed mechanism of impingement in the presence of a cam lesion is impingement on the rim of the acetabulum by this abnormally shaped femoral head or neck in flexion (Fig. 2C, 2D). The impingement is proposed to produce symptoms by crushing the acetabular labrum that surrounds the acetabular rim, and by subsequently damaging the underlying articular cartilage.

Figure 2  
Mechanisms of FAI. Normal morphology from an axial oblique perspective is depicted in (A) with a lack of impingement noted when the femur is flexed anteriorly in (B). A cam deformity (excess bone depicted in gray) in a neutral position is shown in (C), whereas anterosuperior impingement occurs (depicted in red) when the femur is flexed anteriorly in (D). A pincer deformity (excess bone depicted in gray) in a neutral position is depicted in (E), whereas anterosuperior impingement occurs (depicted in red) when the femur is flexed anteriorly in (F). The combination of a cam deformity and a pincer deformity depicted in (G) may result in the contre-coup mechanism depicted in (H) where the point of anterosuperior impingement creates a fulcrum that elevates the femoral head out of the acetabulum and causes postero-inferior impingement.

Pincer Lesion

Abnormality in the shape of the acetabulum, also known as a pincer lesion, is another suggested mechanism for FAI. A pincer is a hinged instrument with 2 short handles and 2 grasping jaws used for gripping. When there is overcoverage of the femoral head by the acetabulum, a cross-sectional image through the acetabulum makes the acetabulum appear like a pincer gripping the femoral head, rather than a cup in which the femoral head rests. Consequently, when a morphologically normal proximal femur is taken to the extremes of physiologically normal flexion in the presence of a pincer lesion, the rim of the acetabulum impinges on the neck of the femur (Fig. 2E, 2F).

Pincer impingement is proposed to produce the same cascade of symptoms, with initial damage occurring at the acetabular labrum and subsequent damage occurring at the underlying articular cartilage. Although the etiology is unclear, pincer impingement is observed to occur more often in women than in men.

Contre-Coup Mechanism

The cam and pincer mechanisms are proposed on the basis of labral pathology in the location of anatomic abnormality, most commonly in the anterosuperior region of the acetabulum. However, some authors report surgical findings of additional labral pathology in the posteroinferior aspect of the acetabulum in the setting of more severe anterosuperior pathology. The authors propose that this occurs via a “contre-coup” mechanism, similar to a contre-coup head injury, in which a brain injury occurs opposite to the side of impact. In contre-coup impingement, the point of anterosuperior contact functions as a fulcrum by which the head of the femur is elevated out of the acetabulum and impacts at an opposite posteroinferior region of the acetabulum (Fig. 2G, 2H). Because pincer impingement generally involves additional posterior overcoverage of the acetabulum, this posteroinferior pathology is observed more often in patients with pincer impingement. However, this mechanism is only proposed based on surgical findings, and no studies performed to date are able to document its occurrence in vivo.
**Findings on Physical Examination**

Although a more thorough discussion of the clinical presentation of FAI is beyond the scope of this review, certain findings on physical examination correlate with the above detailed bony abnormalities. Klaue et al\(^{13}\) first described the anterior impingement test in their description of the “acetabular rim syndrome” in 1991. This test consists of flexion, adduction, and internal rotation of the hip, which places the anterior aspect of the femoral head/neck junction in contact with the anterosuperior acetabulum. The elicitation of pain is considered a positive test for impingement. Two tests can be used to test for posterior impingement. The posteroinferior impingement test is performed by placing a supine patient at the end of the examination table and allowing the affected hip to go into hyperextension. The affected leg is then externally rotated, with the elicitation of pain being considered a positive test for impingement.\(^{18}\) The FABER (flexion, abduction, and external rotation) or Patrick test is performed by placing the affected extremity of a supine patient in the figure-of-4 position of flexion, abduction, and external rotation and then measuring the distance from the lateral aspect of the knee to the examination table.\(^{18}\) An increased distance on the affected side from the lateral aspect of the knee to the examination table compared with the unaffected side is considered a positive test for impingement. When this test elicits pain, anterior groin pain suggests intrarticular hip pathology, while posterior hip pain may indicate sacroiliac pathology.

**Research Techniques**

Although the aforementioned findings are documented, many unanswered questions remain. The underlying causes of the bony abnormalities are not determined, and the mechanical mechanisms of impingement and resulting joint damage are not well understood. Research approaches for the study of FAI consist primarily of cadaveric biomechanical studies and static 2D or 3D imaging. A brief overview of some of these studies follows.

**Cadaveric Studies**

Given the recent development of surgical techniques for resection of the anterolateral aspect of the femoral neck to treat FAI presumed to be caused by a cam lesion,\(^{8,19,20}\) Mardones et al\(^{21}\) evaluated the safety of such techniques with regard to the danger of femoral neck fracture. Fifteen matched pairs of cadaveric proximal femur specimens were divided into 3 groups in which 10%, 30%, or 50% of the diameter of the femoral neck was excised. Although the energy necessary to fracture was inversely proportional to the amount of bone resection and the specimens in which 50% of the femoral neck was resected had a lower peak load to failure, no difference was observed between the 10% and 30% groups with regard to peak load to failure. The authors therefore suggested that no more than 30% of the femoral neck should be resected during osteoplasty. In a follow-up cadaveric study, they found that arthroscopic techniques resulted in resections of similar size to open techniques, but that arthroscopic techniques were less successful in performing the resection in the planned area.\(^{22}\) Zumstein et al\(^{23}\) documented similar difficulties in localizing the site of resection when arthroscopically resecting cadaveric acetabular rims.

**Computed Tomography**

Beaulé et al\(^{24}\) used 3-dimensional computed tomography (CT) to compare the proximal femoral morphology of 30 subjects with painful nondysplastic hips to that of 12 asymptomatic control patients. The mean alpha angle for the symptomatic group was found to be significantly greater in the symptomatic group than in the control group (66.4 vs 43.8, \(P = 0.001\)). The mean alpha angle was also significantly greater for men in the symptomatic group than for women in the symptomatic group (73.3 vs 58.7, \(P = 0.009\)). In addition to providing valuable demographic information, this study demonstrates that CT can be a useful and noninvasive method to study FAI.

Tannast et al\(^{25}\) developed specialized software to predict hip range of motion in plastic models and cadaveric hips, based on CT bone models and validated using computer navigation software previously designed for hip arthroplasty. The study demonstrated accuracy of 0.7 ± 3.18° in a plastic bone setup and −5.0 ± 5.68° in a cadaver setup, presumably because of soft-tissue effects in the cadavers. The authors next used this software to predict the hip range of motion of 21 subjects with FAI and 36 control subjects. Although a similar validation with computer navigation software was not possible because the navigation software required the surgical implantation of reflective markers, the custom software predicted the expected deficits for symptomatic subjects in flexion and abduction from a neutral position and in internal rotation at 90° of flexion (all \(P < 0.001\)). Kubiak-Langer et al\(^{26}\) applied the same research model to the prediction of the results of femoral neck osteoplasty in subjects with FAI and had similar success.

**Magnetic Resonance Imaging**

Wyss et al\(^{27}\) studied the efficacy of MRI in predicting clinical symptoms by comparing the MRI findings and physical examinations of 23 subjects with FAI to those of 40 asymptomatic control patients. As expected, they found a significant decrease in hip internal rotation in the subjects with FAI compared with the control patients (4 ± 8° vs 28 ± 7°, \(P < 0.0001\)). Interestingly, the authors found that there was a strong correlation between internal rotation and a measure that the authors devised to standardize the distance between the acetabular rim and potential zones of impingement on the femoral neck (\(r = 0.97, P < 0.0001\)). This measure, the beta angle, is defined as the angle between a line drawn on axial MRI from the center of the head of the femur to the lateralmost aspect of the acetabulum and a line drawn from the center of the head of the femur to the point where the distance from the bony cortex to the center of the femoral head first exceeded the radius of the femoral head (similar to the measurement used in the alpha angle).
In Vivo Studies

Kennedy et al28 studied hip and pelvic motion in 17 subjects with FAI compared with 14 asymptomatic controls using reflective surface markers during level walking. Although the authors were able to demonstrate decreased pelvic and hip motion in the sagittal and coronal planes in the FAI subjects compared with the controls, this type of study does not allow for accurate assessment of joint contact during activities.29

Directions for Future Research

The previously discussed studies greatly expanded our understanding of the biomechanics of FAI, and hold great potential to translate this into improved clinical care. For example, cadaveric studies, such as those performed by Maradones et al21,22 and Zumstein et al23 are essential to ensure that novel surgical treatment of FAI can be performed safely. Furthermore, the prediction models of Kubiak-Langer et al hold great potential for preoperative planning and reproducible, quantitative assessment of surgical efficacy. However, future biomechanical studies should address 2 major shortcomings in our understanding of FAI: the etiology of the disorder and the nature of impinging joint motion that leads to tissue degeneration.

The Etiology of FAI

First, although FAI is characterized and several treatment options are already developed, the underlying etiology of the observed bony abnormalities are not yet determined. The potential etiologies of this “idiopathic” disease are widespread, ranging from early symptoms of osteoarthritis to mild forms of pediatric disorders, such as slipped capital femoral epiphyses that were unrecognized on initial presentation, to distinct diseases with as yet unrecognized genetic or traumatic origins.30 One potential tool to shed light on the underlying etiology of FAI is the application of more powerful computational models to the analysis of proximal femoral

and acetabular morphology. Although most previous techniques attempted to fit the shape of the head of the femur only to that of a circle on two-dimensional imaging, the work of Anderson et al31 expanded this principle to analyze deviations in the shape of the femoral head from a 3-dimensional sphere using CT reconstructions. This type of analysis holds great potential to help surgeons visualize complex three-dimensional deformities and allow them to use this information for preoperative planning.

Characterizing the Mechanics of Impingement: In Vivo Imaging

FAI is, by nature, a dynamic disorder whereby soft-tissue damage results from abnormal motion of the femur relative to the acetabulum. Although extensive work has been conducted to characterize the bony abnormalities present in FAI and the ensuing clinical sequelae, no studies to date have imaged dynamic FAI in vivo. The hip joint is surrounded by large amounts of mobile soft tissue, and thus poorly suited to the most readily available analytical technique, the attachment of reflective surface markers.29,32,33 For similar reasons, the surgical attachment of reflective markers to bone would improve accuracy34-38 but would be particularly morbid in this region. Surgical implantation of tantalum beads into bone to facilitate radiostereometric analysis is another invasive technique that is generally reserved for patients already undergoing surgical intervention, and thus is not applied to the native hip joint.39-41

Dynamic biplane radiography in combination with model-based tracking is a recently developed technique that attempts to overcome these limitations. In brief, this technique applies a ray-tracing algorithm to project simulated x-rays through a density-based, volumetric bone model (from a subject-specific CT scan), producing a digitally reconstructed radiograph. The in vivo position and orientation of a bone is estimated by maximizing the correlation between the digitally reconstructed radiographs and biplane x-ray images

![Figure 3](image-url) Example of cam impingement. (A) AP radiograph of a 35-year-old male patient with groin pain. An obvious cam lesion is denoted with an asterisk. (B) Axial MRI slice of the same subject, with an anterosuperior labral tear denoted with a “#” sign.
obtained during subject activity. By the use of imaging equipment designed for high frame rates, dynamic joint function can be well characterized for a variety of joints and functional movement activities. This technique was previously validated in the glenohumeral joint, the tibiofemoral joint, the patellofemoral joint, and, recently, in the hip joint.

Figure 3A presents an early subject with cam impingement in an ongoing study of FAI that employs model-based tracking and high-speed, biplane radiography. As seen in Figure 3B, labral pathology is already present although degenerative changes are not yet evident in Figure 3A. Figure 4 demonstrates hip joint contact for the same subject at 40° and 60° of hip flexion. As seen in Figure 4B, decreased anterosuperior joint space occurs at deeper flexion angles because of contact between the anterosuperior acetabulum and the anterior femoral head/neck junction. Although thresholds for predicting symptoms or for providing indications for operative intervention cannot be inferred from this early data, the results of this study will prove invaluable in determining the complex biomechanical interactions of the acetabulum and proximal femur during in vivo FAI.

Conclusions

FAI provides a difficult biomechanical puzzle to solve because the extensive soft tissue surrounding the hip joint has made accurate in vivo biomechanical studies difficult. Advances in imaging techniques have expanded our understanding of the cam, pincer, and contre-coup mechanisms of FAI, and new computational methods for analyzing acetabular and proximal femoral morphology may provide new clues to the underlying etiology of FAI. New in vivo analysis techniques, such as model-based tracking and high-speed biplane radiography will help further characterize FAI and assist in the development of techniques for surgical intervention. Furthermore, these techniques will provide powerful tools with which to assess the efficacy of various interventions in restoring normal joint contact patterns.

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