The Biomechanics of Femoroacetabular Impingement

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Abstract:

Femoroacetabular impingement (FAI) has been proposed as a possible biomechanical etiology of early, idiopathic hip osteoarthritis (OA). Two primary mechanisms have been proposed: cam impingement and pincer impingement. In cam impingement, an abnormally shaped or excessively large femoral head or neck abuts against the anterosuperior acetabulum. In pincer impingement, overcoverage of the proximal femur by the acetabulum results in impingement. In severe cases, a contre-coup mechanism has been suggested whereby an anterosuperior contact point functions as a fulcrum and posteroinferior impingement occurs as the femoral head is levered out of the acetabulum. However, these proposed mechanisms have been based on surgical observation rather than *in vivo* documentation of FAI, and controversy exists as to whether surgical interventions should be based on these theories alone. This review of FAI biomechanics discusses 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. Ultimately, better understanding the biomechanics of FAI may help physicians design interventions that decrease the risk of progression to hip OA.

Key words: Femoroacetabular impingement, hip biomechanics, cam impingement, pincer impingement.

Introduction

Femoroacetabular impingement (FAI) occurs when the head or neck of the femur abuts against the rim of the acetabulum. The principles of hip impingement have long been studied with regards to total hip arthroplasty (THA), in which components must be designed to minimize wear and dislocation [1-3]. Impingement has also been 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. has been 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 have provided the basis for two proposed mechanisms of femoroacetabular impingement: an abnormally shaped (non-spherical) or excessively large femoral head or neck, or overcoverage of the proximal femur by the acetabulum.

While these anatomic features can be easily recognized using readily available imaging techniques, such as plain radiographs, *in vivo* characterization of abnormal contact between the femur and the acetabulum has proven more difficult. Devising and implementing appropriate surgical interventions, therefore, has also been difficult. This review aims 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. 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 [9]. Based on 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 two possible morphologic abnormalities, the cam lesion and the pincer lesion.

Defining the Normal Hip

In describing the biomechanical abnormalities, it is important to understand the criteria by which normal hip morphology is generally described, which has been drawn largely from the study of hip dysplasia [11]. The gold standard in clinical imaging of FAI is the magnetic resonance arthrogram, because it best identifies labral and cartilage pathology [12]. 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 (Figure 1A) [11]. A value greater than 20 degrees is generally accepted to indicate a non-dysplastic 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 [13].

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 for a greater range of motion about the hip (Figures 2A and 2B). The alpha angle has been proposed to evaluate deviations in the sphericity of the femoral head and the normal offset between the femoral head and the femoral neck [14]. 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 (Figure 1B). While the values that indicate pathology are debated, values less than 50 degrees are generally accepted to represent normal proximal femur morphology.

Gosvig et al. have also recently proposed the triangular index (TI) for evaluation of proximal femoral morphology [15]. The TI is calculated by first fitting a circle to the femoral head and measuring the radius of the circle (r). A line is next 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 (Figure 1C). When a radiograph with 1.2 times magnification is used, the proximal femur is classified as abnormal when $R \geq r + 2$ mm. This method has the advantage of requiring only an AP radiograph, but its effectiveness has not been as thoroughly evaluated as the alpha angle.

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" [2]. Some authors have also used the term "pistol grip deformity" when describing this lesion, due to the resulting appearance of the proximal femur on an anteroposterior (AP) radiograph [16].

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 (Figures 2C and 2D) [9]. 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 [10].

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 two short handles and two 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 (Figures 2E and 2F) [9].

Pincer impingement has been 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 has been observed to occur more often in women than in men [17].

Contre-Coup Mechanism

The cam and pincer mechanisms have been proposed based on labral pathology in the location of anatomic abnormality, most commonly in the anterosuperior region of the acetabulum. However, some authors have reported surgical findings of additional labral pathology in the posteroinferior aspect of the acetabulum in the setting of more severe anterosuperior pathology [9, 10]. 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 (Figures 2G and 2H). Because pincer impingement generally involves additional posterior overcoverage of the acetabulum, this posteroinferior pathology has been observed more often in patients with pincer impingement. However, this mechanism has only been proposed based on surgical findings, and no studies performed to date have been able to document its occurrence *in vivo*.

Findings on Physical Exam

While a more thorough discussion of the clinical presentation of FAI is beyond the scope of this review, certain findings on physical exam correlate with the above detailed bony abnormalities. Klaue et al. first described the anterior impingement test in their description of the "acetabular rim syndrome" in 1991 [13]. 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) test is performed by placing the affected extremity of a supine patient in the figure-four 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 as compared to the unaffected side is considered a positive test for impingement.

Research Techniques

While the above findings have been documented, many unanswered questions remain. The underlying causes of the bony abnormalities have not been determined, and the mechanical mechanisms of impingement and resulting joint damage are not well understood. Research approaches for the study of FAI have consisted 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. evaluated the safety of such techniques with regard to the danger of femoral neck fracture. 15 matched pairs of cadaveric proximal femur specimens were divided into three

groups in which 10%, 30%, or 50% of the diameter of the femoral neck was excised. While the energy 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 [21]. Zumstein et al. documented similar difficulties in localizing the site of resection when arthroscopically resecting cadaveric acetabular rims [22].

Computed Tomography (CT)

Beaulé et al. used three-dimensional CT to compare the proximal femoral morphology of 30 subjects with painful non-dysplastic hips to that of 12 aysmptomatic controls [23]. 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 males in the symptomatic group than for females in the symptomatic group (73.3 versus 58.7, $p = 0.009$). In addition to providing valuable demographic information, this study demonstrates that CT can be a useful and non-invasive method to study FAI.

Tannast et al. 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 [24]. The study demonstrated accuracy of 0.7 ± 3.18 degrees in a plastic bone setup and -5.0 ± 5.68 degrees in a cadaver setup, presumably due to 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 using the 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 degrees of flexion (all $p < 0.001$). Kubiak-Langer et al. applied the same research model to the prediction of the results of femoral neck osteoplasty in subjects with FAI and had similar success [25].

Magnetic Resonance Imaging

Wyss et al. 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 controls [26]. As expected, the authors found a significant decrease in hip internal rotation in the subjects with FAI compared to the controls (4 ± 8 degrees versus 28 ± 7 degrees, $p < 0.0001$). 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, was defined as the angle between a line drawn on axial MRI from the center of the head of the femur to the lateral-most 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 al. studied hip and pelvic motion in 17 subjects with FAI as compared to 14 asymptomatic controls using reflective surface markers during level walking [27]. While the

authors were able to demonstrate decreased pelvic and hip motion in the sagittal and coronal planes in the FAI subjects as compared to the controls, this type of study does not allow for accurate assessment of joint contact during activities [28].

Directions for Future Research

The previously discussed studies have 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 al. and Zumstein et al., are essential to ensure that novel surgical treatment of FAI can be performed safely [21, 22, 29]. Furthermore, the prediction models of Kubiak-Langer et al. hold great potential for pre-operative planning and reproducible, quantitative assessment of surgical efficacy. However, future biomechanical studies should address two 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 femoroacetabular impingement has been characterized and several treatment options have already been developed, the underlying etiology of the observed bony abnormalities has not been 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 epiphysis 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. While most previous

techniques have attempted the fit the shape of the head of the femur only to that of a circle on two-dimensional imaging, the work of Anderson et al. has expanded this principle to analyze deviations in the shape of the femoral head from a three-dimensional sphere using CT reconstructions [31]. This type of analysis holds great potential to help surgeons visualize complex three-dimensional deformities and allow them to use this information for pre-operative 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. Though 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 analytic technique, the attachment of reflective surface markers [28, 32, 33]. For similar reasons, the surgical attachment of reflective markers to bone would improve accuracy [34-38], but would be particularly morbid in this region. Surgical implantation of tantalum beads into bone to facilitate radiostereometric analysis (RSA) is another invasive technique that is generally reserved for patients already undergoing surgical intervention, and thus has not been applied to the native hip joint [39-41].

Dynamic biplane radiography in combination with model-based tracked is a recently developed technique that attempts to overcome these limitations. Briefly, 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 (DRR). The *in-vivo* position and orientation of a bone is estimated by maximizing the correlation

between the DRRs and biplane x-ray images obtained during subject activity. By utilizing 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 has previously been validated in the glenohumeral joint [42], the tibiofemoral joint [43], the patellofemoral joint [44], and, recently, in the hip joint [45].

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 degrees of hip flexion. As seen in Figure 4B, decreased anterosuperior joint space occurs at deeper flexion angles as a result 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.

Conclusion

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 radiograph 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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Figures

Figure 1: Normal Hip Morphology

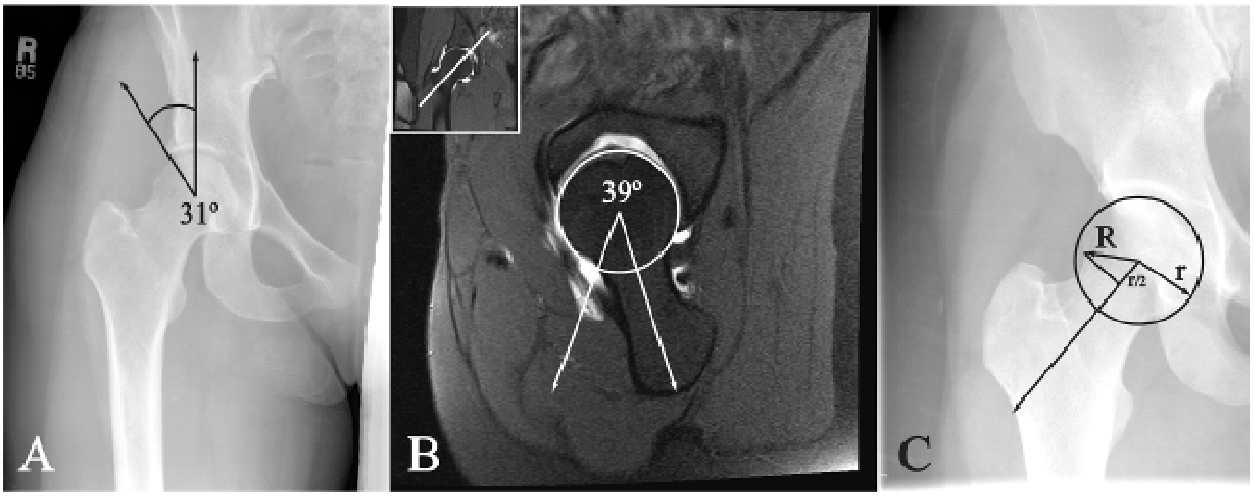

Figure 2: Mechanisms of Femoroacetabular Impingement

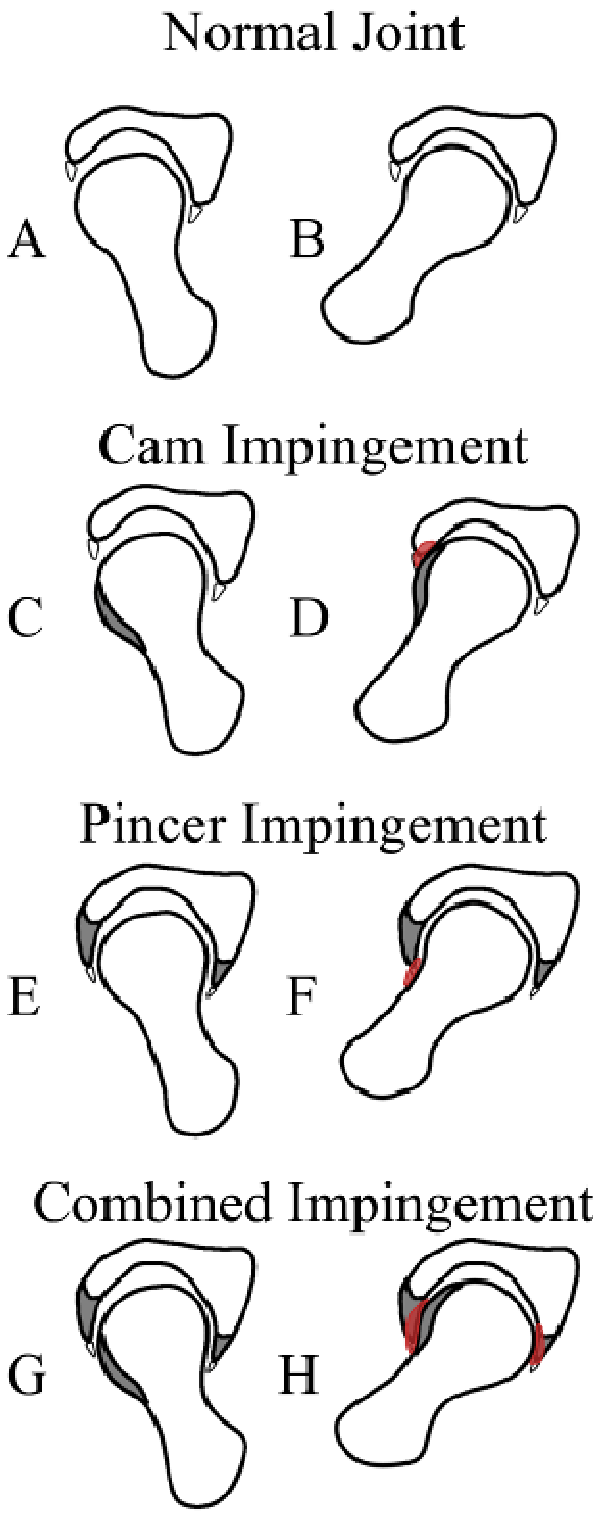

Figure 3: Example of Cam Impingement

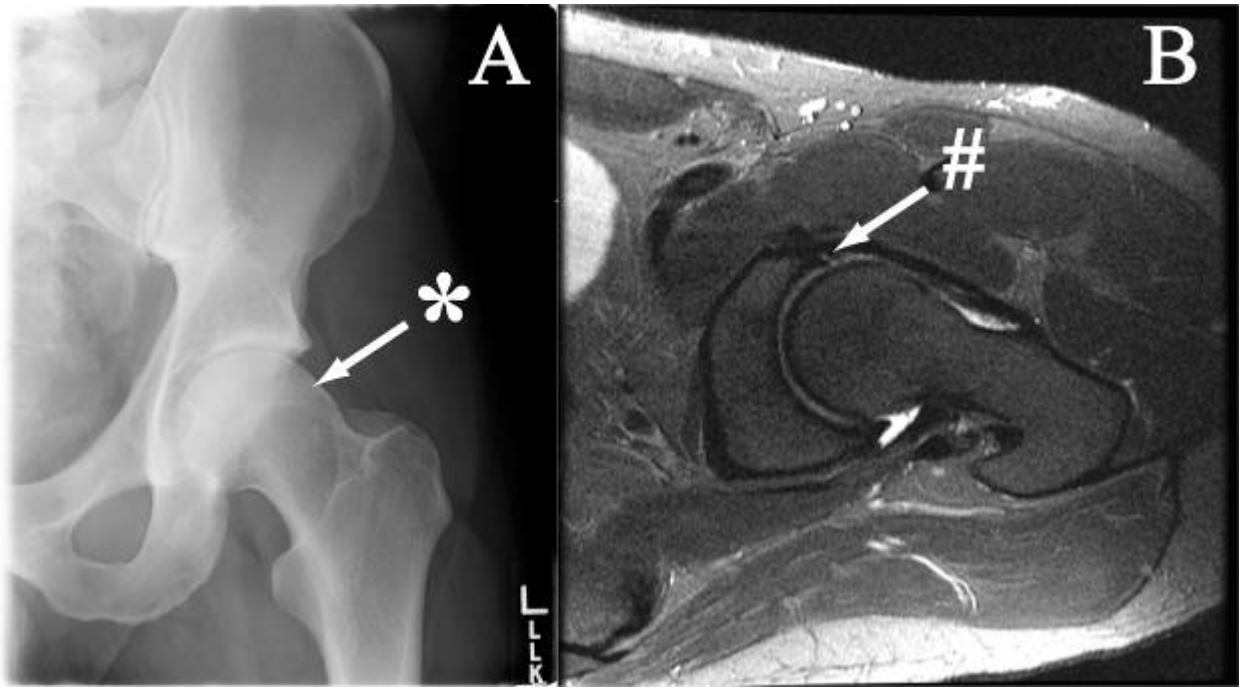

Figure 4: Hip Joint Contact Analysis in Cam Impingement

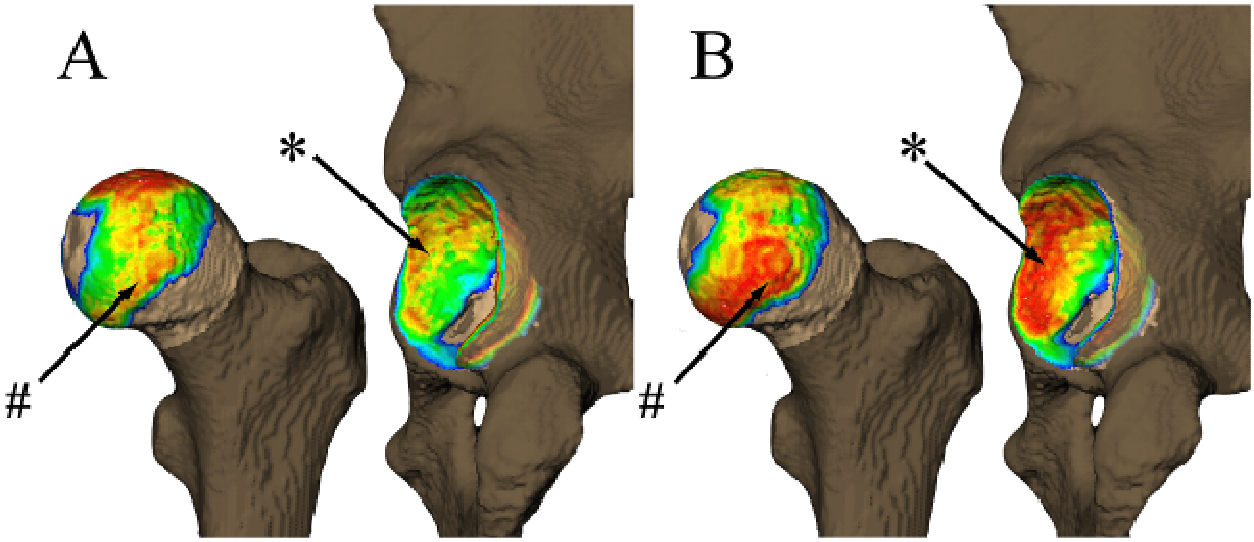

Figure Legend

Figure 1: Normal Hip Morphology. **A**: Anteroposterior (AP) radiograph of a 23 year old female with groin pain. The center-edge angle (CEA) is measured 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 [11]. **B:** Axial oblique slice from magnetic resonance imaging (MRI) of the same subject (orientation of slice illustrated in a coronal slice in the upper-left corner of the image). The alpha angle is measured as the angle 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 sphere fit to the femoral head [14]. **C:** AP radiograph of a 40 year old female with hip pain. The triangular index is calculated by first fitting a circle to the femoral head and measuring the radius of the circle (r). A line is next 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. When a radiograph with 1.2 times magnification is used, the proximal femur is classified as abnormal when $R \geq r + 2$ mm [15].

Figure 2: Mechanisms of Femoroacetabular Impingement. 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 grey) in a neutral position is shown in

C, while anterosuperior impingement occurs (depicted in red) when the femur is flexed anteriorly in **D**. A pincer deformity (excess bone depicted in grey) in a neutral position is depicted in **E**, while 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 posteroinferior impingement.

Figure 3: Example of Cam Impingement. **A:** AP radiograph of a 35 year old male with groin pain. An obvious cam lesion is denoted with a "*." **B:** Axial MRI slice of the same subject, with an anterosuperior labral tear denoted with a "#."

Figure 4: Hip Joint Contact Analysis in Cam Impingement. Joint contact analysis for the subject in Figure 3 at 40° (**A**) and 60° (**B**) of hip flexion. Color scale from 0.1 mm (red) to 5 mm (blue). * = anterosuperior acetabulum, # = anterior femoral head/neck junction.

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