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Original Article

Femoral cam deformity due to anterior capsular force: A theoretical model with MRI and cadaveric correlation

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ABSTRACT

Background: Cam deformity is associated with epiphyseal extension onto the anterosuperior femoral head–neck before physeal closure. A century ago, anatomists speculated that this femoral prominence acts as a pulley bar to withstand capsular compression in hip extension with pressure concentrated where the zona orbicularis (ZO) joins the iliofemoral ligament (IFL). An animal model has shown that growth plates deflect laterally and distally when exposed to forces perpendicular to growth. These observations raise the question of whether capsular pressure against the epiphysis can stimulate cam formation.

Purpose: The purposes are to measure: (1) the distance from the ZO/IFL confluence to the maximal epiphyseal extension (MEE) and cam apex; and (2) acetabular depth at this location, since less coverage increases capsular contact on the physis.

Methods: MRI scans of 39 subjects (47 hips) were measured. Acetabular depth was compared between those with and without a cam deformity. Secondarily, anatomic findings were correlated on a cadaveric specimen.

Results: The cam apex and MEE were adjacent to the ZO/IFL confluence in all subjects (mean, 6.3 mm). Controlling for sex, acetabular depth was less (12.5%, $p = 0.012$) in the group with cam deformity. Contact points were confirmed in the specimen.

Conclusions: The cam apex and MEE occur at the ZO/IFL confluence in the thickest region of the anterosuperior capsule and vary with acetabular depth. This supports a theoretical model postulating that capsular forces against an immature epiphysis may induce cam formation, particularly in individuals who repetitively tension the anterior capsule.

1. Introduction

Femoroacetabular impingement (FAI) is increasingly recognized as a cause of hip pain and risk factor for osteoarthritis.[1] The femoral cam lesion is a developmental deformity[2–5] that is implicated in the labrochondral damage in FAI.[1,6] It is associated with abnormal extension of the epiphysis onto the anterosuperior proximal femur.[5] This epiphyseal extension precedes formation of the cam lesion before physeal closure.[3] Although cam morphology is more prevalent in athletes, the mechanism for its development is unknown.

Anatomists first characterized a bony prominence at the anterior femoral neck in 1899, calling it the 'eminentia articularis colli femoris', or 'eminentia'.[7–9] It was speculated that this fibrocartilage-covered eminentia functions as a pulley bar for the anterior hip capsule when the joint is in a position of extension.[9] Specifically, the most compressive force occurs where the zona orbicularis (ZO) blends with the iliofemoral ligament (IFL) at the medial side (head–neck junction) of the eminentia.[9] Bone morphology is influenced by local and systemic mechanical loading and modulated by the direction, degree and timing of the forces at the epiphyseal growth plates.[10–12] Forces perpendicular to the direction of growth have been shown in both an animal model[11] and a computer simulation[13] to result in lateral displacement of the epiphysis and periosteal apposition.

Noting that the cam lesion is most pronounced at the anterosuperior femoral head–neck junction,[5,14] particularly between 1 and 2 o' clock, which correlates to the thickest part of the

Abbreviations: FAI, femoroacetabular impingement; ZO, zona orbicularis; IFL, iliofemoral ligament; MEE, maximal epiphyseal extension; EER, epiphyseal extension ration; ARA, acetabular roof angle.

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anterior capsule,[15] raises the question whether anterior capsular pressure in this location may stimulate epiphyseal extension and cam formation. As a first step to explore this question, this study investigates the location where the fibers of the iliofemoral ligament and zona orbicularis coalesce with respect to: (1) the maximal epiphyseal extension in the proximal femur in subjects with and without a femoral cam lesion (alpha angle less than 55°), and (2) the apex of the cam deformity in those with the lesion. We then compared acetabular measures between the two groups, since acetabular depth influences the trajectory and degree of contact the capsule has against the proximal femur. The null hypotheses are that there is no correlation between the location of the capsular fiber confluence and the cam or epiphyseal extension, and there is no difference in acetabular depth between groups.

2. Methods

After institutional review board approval, we reviewed the database of new patients evaluated for hip pain at a single institution over a 2-year period from October 2012 through September 2014. We selected those who had undergone MRI scans at our facility and who were between the ages of 15 and 25 to ensure physeal closure and adequate visualization of the physeal scar, and to minimize the possibility of secondary arthritic change. Subjects were excluded if they had previous surgery, trauma, systemic illness that would affect hip growth, or inadequate image sets.

During the study time period, 1424 new patients were evaluated for hip pain, 185 between the ages of 15 and 25. Forty-four underwent MRI in our institution; five were excluded based on the criteria described above. This left 39 subjects (47 hips) for evaluation. Thirty-six hips had alpha angle equal to or greater than 55 (cam group) and 11 had alpha angles less than 55 (normal offset group) measured on MRI radial views.

Our MRI protocol is unique in that patients lie supine with their hips in a position of comfort, rather than forcing internal rotation to correct for femoral anteversion. As such, the location of the hip capsule and proximal femur are considered to be in their natural, resting position. The study was performed on an 18-channel 1.5 T MR system (Magnetom Symphony, Siemens, Erlangen, Germany) using a small flex coil to wrap the hip and large body matrix coil for pelvis imaging. Two-dimensional proton density fat-saturated turbo-spin echo coronal (TR/TE = 3000/37 ms, matrix size = 320 × 320, slice thickness = 3 mm, FOV = 180) and true sagittal (TR/TE = 3000/28 ms, matrix size = 320 × 320, slice thickness = 3 mm, FOV = 180) views were obtained, as well as a 3-dimensional space sequence (TR/TE = 1200/18 ms, matrix size = 250 × 256, slice thickness = 0.80 mm, FOV = 200). Radial and axial oblique images were generated from multiplanar reconstructions correcting for the rotation of the femur. Eighteen radial views were produced with the first slice at the 12 o' clock position of the coronal plane and rotating clockwise in 10° intervals around, and perpendicular to, the femoral neck axis. Axial oblique reconstructions were obtained parallel to the femoral neck at 3 mm slice thickness. Using an Intellispace PACS worksite (Phillips; Andover, MA), the alpha angle and epiphyseal extension were measured on all 10 radial views that comprise the anterosuperior quadrant of the proximal femur (12–3 o' clock) where the epiphyseal extension and cam lesion are most pronounced.[4,5] The radial slice and values for the maximal epiphyseal extension and apex of the cam lesion, if present, were recorded. To correct for variation in femoral head diameter, epiphyseal extension is expressed as a ratio of the distance from the medial femoral head to the epiphyseal line divided by the femoral head diameter as described by Siebenrock and colleagues (Fig. 1a).[5] The acetabular roof coverage was measured on radial views and determined by the angle between a line extending through the center of the femoral head and neck to the acetabulum (a continuation of the line used for the alpha angle measurement) and a second line from the center of the femoral head tangential to the most anterior point of the bony rim (Fig. 1b).

The MRI DICOM files were imported into Osirix (Pixmeo; Geneva, Switzerland), which numerically displays 3-dimensional locations in the scan. The 0 point on the *x*, *y*, *z*-axis corresponds to the isocenter of the magnet when the scan is obtained. This point may vary between subjects, but the 3-dimensional coordinates are accurate for within subject/scan measures. The 3-dimensional coordinates of the maximal epiphyseal extension and the cam apex were recorded from the radial view (Fig. 1c), and the confluence of the superior band of the iliofemoral ligament with the zona orbicularis on the axial oblique views (Fig. 1d).[16] To minimize bias, the two points were recorded at different sessions.

Hips were classified according to the presence or absence of a cam deformity, which was defined as an alpha angle of 55° or greater on any radial slice. The distance measured on MRI between the ZO/IFL and the point of maximum epiphyseal extension was compared between groups with a *t*-test. This calculation was repeated for the distance between the ZO/IFL and the apex of the cam deformity in the subset of patients with alpha angle of 55° or greater. Finally, the acetabular coverage angle at the point of maximum epiphyseal extension was compared between groups using univariable and multivariable regression. The reliability of the MRI measurement technique was evaluated by repeating blinded measurements on ten hips at an interval of 3 months after the original measurement by the same examiner. Ten subjects were randomly selected for repeated measures of the distance on MRI between the ZO/IFL and the point of maximum epiphyseal extension. These measures were then compared to the original measures for these subjects to judge the reliability of the measurement technique. Two methods of assessing reliability were performed – first, direct comparison of the mean distance measurements between measurement episodes, and second, the 95% limits of agreement method of Bland and Altman, and then comparing mean differences in measurements, as well as calculating the Bland–Altman limits of agreement between measurements. Statistical significance was defined as $p < 0.05$; all tests were two-sided.

In the second part of the study, a cadaveric specimen from a 50 year-old male with a cam lesion and no radiographic arthritis was imaged with CT, fluoroscopy and MRI, and then dissected to correlate the imaging findings with the anatomic structures. Finally, the capsule was examined histologically to define the fiber orientation at the confluence of the zona orbicularis and the superior band of the iliofemoral ligament.

3. Results

There was a higher proportion of males in the cam group compared to the normal offset group but no difference between the groups with respect to age, body mass index, side of involvement, or epiphyseal extension ratio (Table 1). In all subjects, the distance from the confluence of the superior band of the iliofemoral ligament and zona orbicularis was in close proximity to the maximal epiphyseal extension (5.7 mm in the cam group and 8.1 mm in the normal offset group; mean 6.3 mm). There was no statistically significant difference in this distance between groups ($p = 0.27$). Similarly, in subjects with an alpha angle greater than 55°, the capsular confluence closely corresponded to the location of the apex of the cam deformity (mean, 4.98 mm; 95% CI 4.00–5.96).

At the location of maximal epiphyseal extension, the acetabular roof angle was larger in the group with normal offset compared to the cam group (70.9° vs. 64.1°, mean difference 6.8°, $p = 0.04$). In multivariable analysis, controlling for sex, the acetabular depth