Symptomatic Femoroacetabular Impingement: Does the Offset Decrease Correlate With Cartilage Damage? A Pilot Study

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Abstract

Background Current measures of the reduced head-neck offset such as residual deformity of slipped capital femoral epiphysis (SCFE) including the alpha angle, which measures the femoral head-neck sphericity but does not account for acetabular abnormalities, do not represent the true magnitude of the deformity and the mechanical consequences. The beta angle (angle between the femoral head-neck junction and acetabular rim) accounts for the morphology of both the acetabulum and femur and, thus, may be the more appropriate parameter for assessing SCFE deformity.

Questions/purposes We determined (1) whether the beta angle could be reliably measured on MRI; and (2) whether the beta angle correlates with the cartilage status.

Methods We recruited 10 adult patients (mean age, 28 years) with symptomatic cam femoroacetabular impingement and 15 asymptomatic volunteers (mean age, 24 years) to have three-dimensional MRI including delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) for cartilage status assessment. Corresponding alpha angles, beta angles, and acetabular dGEMRIC indices were obtained in seven radial reformats to assess the hip in seven regions (anterior to superior and posterior).

Results We noted high reproducibility for both alpha and beta angle measurements. The dGEMRIC indices correlated with beta angles in the superoinferior and superior regions but not the alpha angles.

Conclusions Beta angle measurement in radial MR images is reproducible and appears to correspond to cartilage damage in the superior regions of the hip. The beta angle may be a useful parameter to assess hip deformity in the followup of SCFE although further confirmation is warranted.

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This study was performed at the University Hospital of Düsseldorf, Düsseldorf, Germany.

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Introduction

Slipped capital femoral epiphysis (SCFE), the anterolateral displacement of the metaphysis with respect to the proximal femoral physis, is one of the most common hip disorders in adolescents. The clinical presentation ranges from sudden disability of standing and walking to a complete lack of symptoms [30]. A number of studies [5, 13, 15, 17] suggest an association between residual hip deformity after SCFE and symptomatic femoroacetabular impingement (FAI) with subsequent early development of osteoarthritis (OA).

Early OA is characterized by the loss of the negatively charged glycosaminoglycans (GAG) [2]. Delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) is sensitive to the

charge density in cartilage using a charged form of gadolinium contrast agent (ie, gadolinium-tetraazacyclododecanetetraacetic acid [Gd-DOTA⁻]). Several gadolinium-based contrast agents are available for contrast-enhanced MRI, whereas the double negatively charged contrast agent gadolinium dimeglumine (GdDTPA²⁻) was used in most previously reported dGEMRIC studies. To better incorporate the dGEMRIC technique into clinical routine, we used the single negatively charged contrast agent Dotarem® (Gd-DOTA⁻), which is the standard gadolinium-based contrast agent in many departments because it is stable with regard to its chelate compound and unlikely to cause nephrogenic systemic fibrosis [22]. Furthermore, our group recently suggested dGEMRIC imaging can be performed using a single negatively charged contrast agent [31]. The anionic, negatively charged contrast agent is administered intravenously, in which the subsequent gadolinium uptake into cartilage is inversely proportional to the concentration of GAG [3]. Because gadolinium reduces the MR parameter T1 relaxation time (T1_{Gd}), higher T1_{Gd} values are noted in healthy cartilage in contrast to decreased T1_{Gd} values in degenerated cartilage according to the decrease in GAG.

FAI is an abutment conflict between the proximal femur and acetabulum arising from an offset insufficiency between the proximal femur and acetabulum resulting from a nonspherical shape of the femoral head (cam type), overcoverage of the femoral head by the acetabulum (pincer type), or a combination of both (mixed type) [4, 13]. Common methods to identify a potential impingement conflict between the proximal femur and the acetabulum are: (1) alpha angle (measuring the asphericity at the femoral head-neck junction) [20]; (2) femoral head-neck offset (distance between a tangent to the anterior femoral neck and a parallel tangent to the anterior femoral head) [11]; (3) femoral head-neck offset ratio (ratio between the femoral head-neck offset and the diameter of the femoral head; and (4) the center-edge angle of Wiberg [28] measuring the femoral head coverage.

The recently described beta angle, the angle between the femoral head-neck junction and acetabular rim [8, 29], is less commonly reported than the alpha angle but accounts for the morphology of both the femur and the acetabulum, which is crucial to reliably reflect the magnitude of the deformity and its mechanical consequences. In the original description by Wyss et al. [29], the beta angle (free space between the femoral and acetabular contours) was established with the hip flexed to 90° using an open MRI system. Recently, Brunner et al. [8] reported a technique to measure the beta angle on the basis of plain radiographs. Although both of these techniques consider femoral offset and acetabular overcoverage as integral components of FAI, both techniques have limitations. First, the femoro-acetabular deformity is assessed in a single location.

Therefore, the offset decrease can potentially be underestimated in certain regions. This concern has been outlined by Dudda et al. [10] who noted pathologically increased alpha angles in various radial planes even in hips with normal-appearing radiographs. Second, the technique described by Wyss et al. [29] necessitates an open MRI scanner that is not widely available. However, it is unclear whether a circumferential beta angle assessment using three-dimensional (3-D) MRI and multiplanar reformatting allows precise localization of the FAI pathology.

We therefore determined whether: (1) the beta angle could be reliably measured on MRI with multiplanar reformatting evaluating the relationship between proximal femur and acetabulum over the full upper 180° of the hip; and (2) whether circumferential beta angle values correlate with corresponding acetabular dGEMRIC indices.

Patients and Methods

We identified 10 adult patients (seven men, three women; mean age, 28 ± 6.7 years; range, 18–40 years; mean body mass index [BMI], 23.5 kg/m²; range, 20.0–26.2 kg/m²) with symptomatic cam FAI, none of whom had any history or imaging findings consistent with symptomatic SCFE. The diagnosis of cam FAI was confirmed by patient history, physical examination (positive anterior impingement test), and radiographic evaluation [19] by means of a standard pelvic AP and a Lauenstein radiograph. The diagnosis of cam FAI was further confirmed by an alpha angle in the Lauenstein radiograph of more than 50°. We included patients with no radiographic findings of OA (Tönnis Grade 0 [25], n = 8) and those with Tönnis Grade 1 changes (n = 2). Patients with moderate to severe OA (Tönnis grade > 1) were excluded from this study because severe cartilage loss can compromise region of interest (ROI) analyses for T1_{Gd} quantification. We also excluded patients with any concomitant hip abnormalities besides cam FAI and those with contraindications for undergoing MRI with intravenous gadolinium contrast. A control group included 15 healthy volunteers (four men, 11 women; mean age, 24 ± 1.8 years; range, 21–29 years; BMI, 20.8 kg/m²; range, 17.6–25.0 kg/m²) without any obvious underlying hip disorders. Volunteers with incidental asymptomatic cartilage degeneration on morphologic MRI (n = 0) were excluded from this study.

Two of us (BB, CZ) reviewed the medical history and performed physical examinations. The same two individuals evaluated the radiographs to reach consensus on diagnosis (cam FAI) and radiographic hip joint status (OA grade according to the Tönnis classification). One radiologist (FM) with expertise in hip imaging and cartilage

assessment confirmed normal cartilage in the control group based on the MRI.

MRI was performed on a 3-T system (Magnetom Trio; Siemens Medical Solutions, Erlangen, Germany) with a flexible body-matrix phased-array coil. The subjects were examined in the supine position with the hip of interest held in neutral position supported by foam and adjustable straps. Subsequent to the intravenous injection of FDA-approved Gd-DOTA⁻ (0.4 mL/kg, 0.2 mmol Gd/kg, Dotarem; Guerbet GmbH, Sulzbach, Germany), the subjects were encouraged to walk around and move the hip actively, trying to achieve the full ROM in all directions until MRI was continued 45 minutes after the contrast injection [9].

The MRI protocol included a 3-D double-echo steady state (DESS) sequence with water excitation for morphological cartilage assessment [14], a B1 prescan for field inhomogeneity correction [1, 24], and a dual flip angle 3-D gradient echo sequence with volumetric interpolated breathhold examination for T1_{Gd} (dGEMRIC index) assessment [18, 26]. T1_{Gd} maps were derived from an inline processing package (SyngoMapIt; Siemens Medical Solutions), which uses a nonlinear least square fitting routine. Geometric imaging parameters (image resolution, field of view) were similar for both DESS and T1_{Gd} imaging. Further details on the imaging parameters are provided (Table 1). The 3-D data sets of DESS and volumetric interpolated breathhold examination, which included the inline 3-D T1_{Gd} maps, were transferred to a Leonardo[®] workstation (Siemens Medical Solutions) for further analyses. Similar to previously performed studies [6], seven 2-mm thick radial reformats (anterior, anterosuperior, superoanterior, superior, superoposterior, posterosuperior, and posterior), which were concentric within the center of the femoral head and perpendicular to the acetabulum, were generated from the 3-D data sets by using multiplanar reconstruction software (Fig. 1).

Subsequently, alpha angle, beta angle, and cartilage T1_{Gd} assessments were performed on each radial reformat. Two orthopaedic surgeons (CZ, BB) independently determined the alpha angles as described by Nötzli et al. [20]. A best fit circle around the perimeter of the femoral head was drawn. Femoral head center, the point where the distance from the bone to the center of the femoral head first exceeds the radius of the subchondral femoral head (point A), and the axis of the femoral neck, which is defined as a line passing through the center of the femoral head and the center of the neck at its most narrow point, were identified. Subsequently, an angle was drawn between a line from the center of the femoral head through the axis of the femoral neck and a second line connecting the center of the femoral head with point A

Table 1. Imaging parameters of the 3D DESS and VIBE (dGEMRIC) sequence*

Parameter	3D DESS water excitation	3D VIBE
Repetition time (ms)	14.75	15
Echo time (ms)	5.03	2.24
Flip angle (°)	25	5°, 26°
Number of excitations	1	1
Field of view (mm ²)	192	192
Slice thickness (mm)	0.6	0.6
In-plane resolution (mm)	0.6 × 0.6	0.6 × 0.6
Slice gap (mm)	0.2	0.12
Bandwidth (Hz/pixel)	260	260
Aquisition time (minutes)	13.17	14.31

* The isotropic resolution of 0.6 mm³ allowed sufficient distinction between acetabular and femoral cartilage; 3D = three-dimensional; DESS = double-echo steady state; VIBE = volumetric interpolated breathhold examination.

(Fig. 2A). The same observers measured the beta angle as described by Wyss et al. [29]: angle between a line drawn from the center of the femoral head to point A and a second line to the lateral bony margin of the acetabulum (Fig. 2B). One of the two readers (BB) repeated the measurements after 4 weeks to assess intraobserver reliability. We determined intra- and interobserver reliability using intraclass correlation coefficients.

As a marker of cartilage degeneration [6] we used the dGEMRIC index (T1_{Gd} in ms) at the peripheral zone of each radial reformat by means of ROI analyses, whereas the peripheral ROI was defined as the lateral half of the acetabular cartilage. Corresponding DESS reformats served as a morphological reference to warrant correct placement of the ROI squares within cartilage bounds (Fig. 3). All T1_{Gd} measurements were performed by two orthopaedic surgeons (CZ, BB) with expertise in interpreting dGEMRIC MRI. A total of 175 ROIs were analyzed, whereas four ROIs were excluded because they were compromised by imaging artifacts. Therefore, 171 ROIs were further analyzed. Mean size of the ROIs was 0.09 ± 0.03 cm² (24 ± 9 pixels) ranging from 0.03 cm² (eight pixels) to 0.18 cm² (50 pixels).

Mean values, SD (±), and ranges were obtained. The Student's t-test (independent samples) was applied to test for differences between the alpha angles, beta angles, and T1_{Gd} values of the patient group and the control group. Pearson correlation (two-tailed, absolute agreement) analysis was performed to test for correlations between acetabular cartilage damage (dGEMRIC index, T1_{Gd} in ms) and femoroacetabular morphology assessed either with the alpha angle or the beta angle in

Fig. 1 Radial reformats with an interval of 30° reaching from anterior to superior and then to posterior were derived by multiplanar reconstruction (MPR): a = anterior; a-s = anterosuperior; s-a =

superoanterior; s = superior; s-p = superoposterior; p-s = posterosuperior; p = posterior instead of clock positions for both right and left hips.

various regions of the hip. SPSS® software (Version 19.0; SPSS, Inc, Chicago, IL, USA) was used for statistical analyses.

Results

Intraclass correlation analyses revealed intra- and interobserver ICCs for the alpha angle of 0.933 and 0.916, respectively, and for the beta angle of 0.924 and 0.905, respectively.

The patient group revealed (1) substantially lower T1_{Gd} times in all regions (Fig. 4); (2) substantially higher alpha angles in all regions except for the posterosuperior and posterior regions; and (3) lower beta angles in the anterior, anterosuperior, and superoanterior regions (Table 2). The beta angle correlated with the dGEMRIC index in the superoanterior ($r = 0.650$; $p = 0.042$) and superior ($r = -0.671$; $p = 0.034$) regions (Fig. 5A), whereas the alpha angles did not correlate with the dGEMRIC indices (Fig. 5B).

Discussion

Slipped capital femoral epiphysis is strongly correlated with an insufficient femoral head-neck offset and a cam

morphology that may induce the development of symptomatic FAI. However, this only reflects the femoral side and, as noted in previous and recent studies on SCFE and FAI, the acetabular morphology itself may be another cause for impingement related to acetabular overcoverage and/or acetabular retroversion. Notably, the acetabula in patients with SCFE reportedly have greater coverage [23] and are more prone to retroversion [12] than age-matched control subjects. Therefore, it is crucial not only to consider the femoral, but also the acetabular morphology to alert clinicians to the potential of developing FAI after SCFE. The beta angle among the head-neck junction, the center of the femoral head, and the acetabular rim takes both proximal femur and acetabulum into consideration and thus might be a more reliable predictor for offset pathology, resulting mechanical consequences, and secondary cartilage damage. The purpose of this study was to evaluate whether the beta angle could be reliably measured on MRI reformats and whether beta angle values throughout the hip correlate with corresponding acetabular dGEMRIC indices.

Our study has limitations. First, the small sample size of this study does not allow us to establish normal values for beta angles throughout the hip. Therefore, larger study cohorts will be necessary. Second, although we have provided MR correlation of cartilage status, this study lacks the validation to a gold standard such as intraoperative

Fig. 2A–B Alpha angle and beta angle measurements in radial MRI of two patients depicting the superior region in Patient 1 (A) and the anterior region in Patient 2 (B). Note both regions reveal similar alpha angles ($\sim 73^\circ$) but remarkable differences in beta angles.

Fig. 3A–B Double-echo steady state (DESS) (A) and corresponding $T1_{Gd}$ reformat (B) for ROI analysis of peripheral acetabular cartilage. DESS reformats served as a reference for the correct ROI placement within cartilage bounds.

assessment and histological analysis to assess the cartilage status. Further studies are needed to establish normal $T1_{Gd}$ values, which are essential before studies with intraoperative cartilage morphology assessment are performed. However, cartilage status assessment with dGEMRIC is reportedly reliable [7]. Third, because this study was conducted on adult patients with cam FAI without an obvious known history of SCFE in childhood, these findings cannot be directly extrapolated to hips in SCFE, although the resulting cam morphology can lead to symptomatic FAI. Notably, in SCFE, the center of the deformed femoral head may no longer be collinear with the midfemoral neck axis and, thus, angle measures such as the alpha and beta angle, which rely on the center of the femoral head as a reference

point, may be potentially distorted. This also applies for the creation of radial images, where, in cases of severe slippage, it is appropriate to use the center of the femoral neck as the axis of rotation. Fourth, our study group included a relatively large number of females with a pure cam lesion that does not reflect the reported distribution of the various types of FAI in male and female patients [13]. For this pilot study we recruited a small number of consecutive patients with isolated cam FAI who presented to our outpatient clinic, and therefore the female/male ratio of patients with cam FAI in this study is not representative. However, with regard to the aim of this study to determine 1) whether the beta angle can be reliably measured on MRI and 2) if the beta angle values correlate with the cartilage status, the

Fig. 4A–C dGEMRIC indices (T1_{Gd} in ms) (A), alpha angles (B), and beta angles (C) presented as mean values in patients with cam FAI and asymptomatic volunteers in various regions of the hip. Note the lower T1_{Gd} values in the study group in all regions indicating cartilage degeneration throughout the joint (A). The alpha angle plots

reflect the femoral offset decrease typically present at the anterior to superior regions (B). The beta angle plot in the volunteer group resembles a straight line, whereas a notable spike can be seen in the superoanterior and superior regions where the impingement and cartilage damage are most likely to occur in cam FAI (C).

influence of the female/male ratio on the study results may be negligible. Fifth, the beta angle evaluates the spatial relationship between the femoral head-neck junction and the acetabular rim on multiple radial reformats using an imaging protocol in which the hip is in neutral position and not in a position where the actual impingement would occur. Similar to other measuring methods for FAI diagnosis (Table 3), this measurement remains static and does not account for the dynamic process of hip impingement. As such, two structures that are close to one another in one position may not necessarily be engaging each other in

other positions. Therefore, it is possible that pathological alpha and/or beta angles (eg, at the anterior region) correspond to decreased T1_{Gd} values in other regions (eg, superiorly).

We found the beta angle measurement is reproducible for detecting acetabular cartilage damage in the superoanterior and superior regions. We found no correlation between alpha angle measurement and cartilage status assessment despite increased alpha angles, in particular in the characteristic zone (anterior to superior) of impingement. Notably, in the control group, we recognized a

Table 2. Mean values and SDs for T1_{Gd} (ms), alpha angles, and beta angles (°) for volunteers and patients in various regions of the hip*

Region	T1 _{Gd}			Alpha angle			Beta angle		
	Volunteer	Patient	p value	Volunteer	Patient	p value	Volunteer	Patient	p value
a	585.3 ± 79.8	446.1 ± 111.3	0.002	42.9 ± 5.2	54.1 ± 9.4	0.001	91.9 ± 7.2	83.3 ± 12.4	0.044
a-s	592.2 ± 86.2	437.5 ± 115.8	0.001	46.8 ± 4.7	57.5 ± 5.9	< 0.001	80.9 ± 12.4	73.5 ± 10.4	0.014
s-a	603.9 ± 92.0	436.9 ± 113.8	< 0.001	49.3 ± 4.3	63.7 ± 3.8	< 0.001	65.1 ± 8.0	51.0 ± 10.9	< 0.001
s	721.2 ± 117.7	494.8 ± 131.6	< 0.001	46.9 ± 4.2	56.3 ± 14.2	0.023	60.4 ± 7.6	50.3 ± 19.7	0.084
s-p	644.4 ± 90.0	485.4 ± 140.0	0.002	40.6 ± 4.8	51.2 ± 10.9	0.003	56.3 ± 7.9	47.6 ± 16.5	0.089
p-s	619.7 ± 83.9	465.3 ± 146.2	0.003	38.9 ± 3.6	40.1 ± 3.9	0.448	39.8 ± 7.9	40.3 ± 10.0	0.905
p	560.6 ± 79.6	464.2 ± 136.6	0.048	40.7 ± 6.3	38.0 ± 3.2	0.448	29.2 ± 6.6	31.0 ± 11.9	0.661

* Student's t-test - calculated p values revealed statistically significant differences between patients with cam femoroacetabular impingement and healthy volunteers in several regions of the hip; a = anterior; a-s = anterosuperior; s-a = superoanterior; s = superior; s-p = superoposterior; p-s = posterosuperior; p = posterior.

Fig. 5A–B Scatterplot with alpha angle (A) or beta angle (B) and dGEMRIC index (T1_{Gd} in ms) including regression line, correlation coefficient, and p value in the superior region of acetabular cartilage. Only the beta angle correlated with ($r = -0.671$; $p = 0.034$) the dGEMRIC index (B) whereas the alpha angle did not correlated with ($r = -0.607$; $p = 0.063$) the dGEMRIC index (A).

T1_{Gd} pattern of higher values superiorly that reflects the higher GAG content in these weightbearing regions [27, 31]. In contrast, a trend of lower T1_{Gd} values in the entire joint compared with the control group was noted in the study group of patients with cam FAI. This observation is similar to the results of Bittersohl et al. [6] who revealed a pattern of zonal variation, which seems to be unique for the various types of FAI. Although previously reported studies reported a weak correlation ($r = -0.36$) between alpha angles and femoroacetabular dGEMRIC indices [16] and a slightly stronger correlation ($r = -0.483$) between alpha angles and acetabular dGEMRIC indices [21], we found no correlation between alpha angle values and the dGEMRIC indices. Although the reason for this discrepancy cannot be completely explained, the patient population and methods in these studies differed from ours. In the study of Jessel et al. [16], 30 patients (37 hips; mean age, 25 years; range, 13–48 years) with either a combined or cam FAI type were included. The amount of radiographic arthritis according to the Tönnis classification system was mild (Tönnis Grade 0 or 1) in the majority of the hips ($n = 26$). The amount of radiographic arthritis in the remaining 11 hips is not provided. Of note, this study by Jessel et al. had limitations at 1.5 T with resolution-associated inability to differentiate acetabular from femoral cartilage. Therefore, ROI analysis in this study alluded to acetabular and femoral cartilage as one entity in which inclusion of gadolinium-containing joint fluid mapping may have underestimated the T1_{Gd} values in certain areas. Of 32 middle-aged subjects (mean age, 52 years), Pollard et al. [21] identified 24 individuals with a genetic predisposition for the development of hip osteoarthritis and eight control subjects (subjects' spouses). One hip per individual was scanned in which 19 hips revealed a cam deformity (defined by an alpha angle $> 62.5^\circ$), whereas 13 hips were classified as being normal (alpha angle $\leq 62.5^\circ$). In this study, dGEMRIC was performed on a 3-T system, which

Table 3. Assessment of bony anatomy between proximal femur and acetabular rim

Variable	Nötzli et al. [20]	Wyss et al. [28]	Dudda et al. [10]	Brunner et al. [8]	Current study
Title	The contour of the femoral head-neck junction as a predictor for the risk of anterior impingement	Correlation between internal rotation and bony anatomy in the hip	Do normal radiographs exclude asphericity of the femoral head-neck junction?	The plain β -angle measured on radiographs in the assessment of FAI	Femoroacetabular offset in symptomatic FAI: does the offset decrease correlate with cartilage damage?
Year	2002	2007	2009	2010	2013
Angle	Alpha angle	Beta angle	Alpha angle	Beta angle	Beta angle
FAI hips/control hips	39/35	32/40	58	50/50	10/15
Definition	Concavity at the femoral head-neck junction	Arc of congruent internal rotation available with the hip in 90° of flexion	Concavity at the femoral head-neck junction	Angle between the femoral head-neck junction and acetabular rim	Angle between the femoral head-neck junction and acetabular rim
Imaging modality	Axial MRI	MRI in 90° of hip flexion	Radial MRA	Radiographs in 90° of hip flexion	Radial MRI
Key message	FAI hips have less concavity at the femoral head-neck junction than normal hips	Internal rotation is related to skeletal anatomy and can be used to predict the risk of impingement	Without radial MRA slices, the asphericity would be underestimated in patients with FAI patients.	Valid, reproducible and cost-effective alternative to open MRI in the assessment of the pathological bony anatomy in patients with FAI	Circumferential beta angle measurement in radial MR images is feasible and reliable; the beta angle appears to be a predictor for cartilage damage in the superior regions

FAI = femoroacetabular impingement; MRA = MR arthrography.

allowed for acetabular and femoral cartilage distinction. However, in contrast to our study, 15×3 -mm sagittal dGEMRIC images were generated to obtain $T1_{Gd}$ values (dGEMRIC indices) in two ROIs. One ROI was the acetabular cartilage on the three most lateral analyzable slices reflecting the anterior to superior quadrant (12 o'clock to 3 o'clock). The second ROI was the total cartilage (acetabular and femoral cartilage as one entity) from anterior to superior and posterior on all analyzable sagittal slices. The unique feature of our study is the radial assessment throughout the hip, which enabled us to precisely characterize the deformity and the corresponding $T1_{Gd}$ pattern from anterior to superior and posterior. This is in contrast to the mentioned studies, in which a fairly gross ROI was selected for $T1_{Gd}$ assessment for subsequent alpha angle/dGEMRIC correlation analyses.

In this study on adult patients with symptomatic cam FAI with early OA, we found a potential of the circumferential beta angle assessment as a surrogate for femoroacetabular offset in FAI. The beta angle measurement in radial MR images is reliable and may predict cartilage damage. Further studies that comprise a larger study sample and a detailed radiological examination of the hip are needed to provide normative data on beta angles in the various regions of the hip. A diagnostic gold standard, which includes intraoperative assessment and histological analysis for cartilage status assessment, is warranted to confirm our findings.

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