



Three-Dimensional Measures of Bony Resection During Femoral Osteochondroplasty Are Related to Alpha Angle Measures: A Cadaveric Study

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Purpose: To determine whether 3-dimensional (3D)—reconstructed proximal femoral bone models can be used to quantify femoral osteochondroplasty and to determine whether the 3D-based metrics are related to clinical alpha angle measures. **Methods:** Six cadaveric specimens with cam-type morphology underwent open femoral osteochondroplasty. Alpha angles were measured on the oblique axial computed tomography slice before and after femoral osteochondroplasty. Preoperative and postoperative computed tomography—based 3D reconstructed femur models were generated for each cadaveric specimen. A 3D-3D registration technique was used to merge the preoperative and postoperative models to measure the surface-to-surface distance between the model surfaces. Bivariate correlation analyses were used to determine the correlations between the preoperative, and the difference between the preoperative and postoperative alpha angle (Δ alpha angle) measures and each of the femoral osteochondroplasty variables of surface area (mm^2), volume (mm^3), maximum height (mm), and mean height (mm). The strength of the bivariate correlations was defined as follows: weak 0.1 to 0.3, moderate 0.3 to 0.5, and strong as 0.5 to 1.00. **Results:** Bivariate correlations revealed a strong positive correlation between preoperative alpha angle with femoral osteochondroplasty volume ($r = 0.899$, $P = .007$) and surface area ($r = 0.899$, $P = .007$). No significant correlations were found between the change in alpha angle and the osteochondroplasty variables. **Conclusions:** In this study, pre- and postoperative 3D bone models could be used to quantify femoral osteochondroplasty and to determine if the 3D-based metrics are related to clinical alpha angle measures. **Clinical Relevance:** 3D-reconstructed image bone models may be helpful to ensure that adequate femoro-plasty is performed intraoperatively, in particular with arthroscopic approach in which visualization may be challenging due to capsular management issues and surgeon experience.

Femoral osteochondroplasty for cam-type morphology is commonly performed during hip arthroscopy in patients with femoroacetabular impingement syndrome (FAIS) and has been shown to

be an effective treatment to eliminate hip pain and improve functional status.¹⁻⁶ It is of prime importance for surgeons to perform a comprehensive bony resection of cam-type morphology to achieve successful

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postoperative outcomes in these patients. Numerous studies have shown that residual cam-type morphology is the primary reason for revision hip arthroscopy.⁷⁻¹⁰ Typically, surgeons performing arthroscopic osteochondroplasty rely on a combination of intraoperative fluoroscopy and dynamic examination of the hip under direct visualization to assess adequate femoral resection. A current question that faces the field of hip arthroscopy is, "what defines an adequate femoral osteochondroplasty resection?"¹¹ Unfortunately, the vast majority of studies that describe postoperative clinical outcomes fail to report the postoperative radiographic parameters, thereby adding to the challenge of establishing a metric for adequate bony resection in patients with FAIS with cam-type morphology.

The alpha angle (AA) is the primary metric for defining the severity of cam-type morphology and is used to evaluate bony resection following hip arthroscopy. AA measures have been established using a variety of imaging modalities and can be assessed on multiple imaging views.¹²⁻¹⁹ However, a threshold to define pathologic morphology on each imaging modality, as well as the most appropriate view for a comprehensive cam assessment, is still under debate. Although Nötzli et al.²⁰ have suggested that a postoperative AA cutoff of 42° should be used to define adequate bony resection of cam-type morphology, a universally agreed-on and standardized threshold is also lacking.

Although its clinical use is primarily qualitative for preoperative planning, 3-dimensional (3D) image reconstruction methods for the quantification of femoral morphology also have been established.^{21,22} The 3D volumetric quantification of cam-type morphology has been shown to demonstrate better inter- and intraobserver reliability than the AA measure, which reveals the potential importance of these measures for clinical practice. The primary application of 3D-reconstructed images has been for surgical planning; however, these techniques also may provide avenues for the development of methods to improve the quantification of osseous pathomorphology, such as cam-type FAIS. Therefore, 3D-reconstructed image models may offer valuable insight regarding important aspects of these pathologic 3D morphologies that are not yet well recognized with existing imaging measures.^{18,23,24}

Image registration techniques are useful for comparing 3D models generated from different imaging modalities, such as computed tomography (CT) or magnetic resonance imaging (MRI) scans. The method Ochia et al.,²⁵ named volume merge, has been validated for use in a number of musculoskeletal applications. These 3D-3D registration techniques also allow for the ability to compare the differences between 2

merged 3D surface models, thereby being able to compare differences in surface shape between the models. Malloy et al.¹⁸ used these techniques to validate the use of 1.5T MRI scans to generate accurate 3D models, which provides the opportunity for the assessment of femoral morphology without the need to expose patients to ionizing radiation. These findings have both profound preoperative and postoperative clinical implications, and, combined with 3D modeling techniques, open the door to provide a deeper understanding of these abnormal 3D morphologies and the relationship between femoral structure and clinical imaging measures. The purposes of this study were to determine whether 3D-reconstructed proximal femoral bone models could be used to quantify femoral osteochondroplasty and whether the 3D-based metrics are related to clinical AA measures. We hypothesized that a larger preoperative alpha angle would be correlated with a greater amount of bone surface area and volume resected during an open femoral osteochondroplasty.

Methods

Cadaveric Specimens

The present study was entirely cadaveric. As such, institutional review board approval was not a study requirement. Six fresh-frozen cadaveric hemipelvises with radiographic evidence of cam-type morphology defined by an AA >55° and no evidence of hip osteoarthritis defined by a Tönnis grade >1 were procured through an accredited tissue bank (ScienceCare, Phoenix, AZ). The exclusion criteria were history of metastatic cancer to the bones and previous surgical intervention performed on the pelvis or proximal femur. The sample size was based on a previous similar investigation.¹⁸ All specimens were evaluated by 2 orthopaedic surgeons (S.N. and S.S.), and no specimens were excluded from the study. The donor age and body mass index averages were 62.6 ± 18.0 years and 25.4 ± 7.8 kg/m², respectively. All cadaveric specimens were stored in a laboratory freezer at -20°C and were removed 48 hours before imaging and testing to ensure complete thawing.

CT Image Acquisition and Segmentation

Each intact thawed cadaveric hemipelvis underwent preoperative and postoperative CT imaging (GE Healthcare; BrightSpeed, Waukesha, WI). The CT scan acquisition used the following scan parameters: 120 kV, 250 mAs, slice thickness of 0.625 mm, and 512 × 512 acquisition matrix. All CT images were exported as Digital Imaging and Communication in Medicine files and stored in our institutional Pictures Archiving and Communication System. A semi-autosegmentation process was performed using commercially available segmentation software (Mimics, version 21; Materialise

Research, Leuven, Belgium). All segmentations were performed by a trained biomedical engineer. CT-based 3D-reconstructed hip models were produced and reviewed to plan the femoral osteochondroplasty.

Open Hip Femoral Osteochondroplasty

Following preoperative CT imaging, tissue removal was performed through dissection beginning in the prone position. All extracapsular soft tissues were dissected from each specimen, the joint capsule was removed, and the labrum was left intact. The cam morphology was assessed on preoperative scans and the deformity was outlined using a surgical marking pen before surgery and reviewed by 2 orthopaedic surgeons (SS and SJN). A single orthopaedic surgeon (SS) performed all operative procedures. A 5.5-mm burr was used to resect the identified cam lesion. After each specimen underwent open femoral osteochondroplasty, a postoperative CT scan was performed on the femoral specimen. The postoperative 3D reconstructed femoral models were produced and reviewed to ensure complete resection of abnormal bony morphology.

Femoral AA Measures

The preoperative and postoperative AA were measured on oblique axial CT slices as previously described.²⁰ To summarize, the oblique axial sequence slice was chosen when the center of the femoral neck was best visualized while maintaining circumferential roundness of the femoral head. A Mose circle was drawn around the sclerotic region of the femoral head. A line was then drawn from the center of the Mose circle through the middle of the femoral neck. A second line was then drawn from the center of the Mose circle to the point where the femoral head loses sphericity with respect to the Mose circle. The angle between both lines forms the AA (Fig 1). The change in AA following the open femoral osteochondroplasty was calculated as the difference between preoperative AA and postoperative AA.

Femoral Osteochondroplasty Measures Based on 3D-Reconstructed CT Femoral Surface Models

3D geometry of the pre- and postoperative femoral osteochondroplasty CT models was compared by measuring surface-to-surface least distance distribution between each pair of superimposed models. The surface-to-surface subtraction algorithm was previously used to validate preoperative 1.5T MRI proximal femoral bone models, which demonstrated absolute agreement with bone models generated by CT imaging.¹⁸ In this study, the same surface to surface comparison was used, with the addition of an intervention to compare the preoperative and postoperative surfaces and quantify the boney resection. Superimposition of the two 3D models was performed by 3D-3D

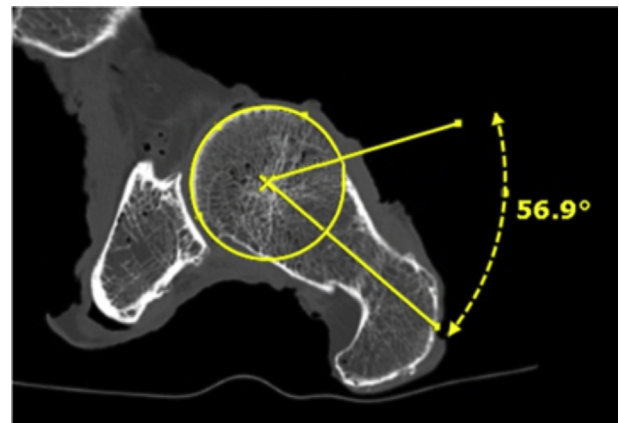


Fig 1. Alpha angle measurement on the oblique axial slice of computed tomography scan.

registration using a validated volume merge method (accuracy, translation: 0.1 mm, rotation: 0.2°).²⁵ The surface-to-surface least distance between the two 3D models was calculated by a point-to-surface distance calculation algorithm using a custom-written program coded in Microsoft Visual C++ 2015 with Microsoft Foundation Class programming environment (Microsoft Corp., Redmond, WA). The femoral osteochondroplasty region was defined as a 3D space at the head–neck junction created by surfaces of pre- and postfemoral osteochondroplasty models with a gap distance over 0.5 mm considering the CT resolution. The femoral osteochondroplasty surface area was defined as the surface area of the post-osteochondroplasty surface (Fig 2).

Statistical Analysis

Before analysis, all data were inspected to evaluate the assumptions for parametric statistical analysis. In cases of assumption violation, the nonparametric statistical analysis tests were performed. The variables of interest in the current study were the AA measured before (pre-AA) and after (post-AA) the osteochondroplasty and the change (Δ AA) in the alpha angle, and the femoral osteochondroplasty measures of: femoral osteochondroplasty volume (mm^3), osteochondroplasty surface area (mm^2), maximum osteochondroplasty height (FH max; mm), and mean osteochondroplasty height (FH mean; mm). A paired samples *t* test was used to evaluate mean differences in AAs before and after open femoral osteochondroplasty. Pearson's (*r*) product moment coefficients and Spearman rank coefficients were used to determine the correlations between the preoperative, and the difference between the preoperative and postoperative alpha angle (Δ AA) measures and each of the femoral osteochondroplasty variables. All data are reported as means and standard deviations. A significance level of

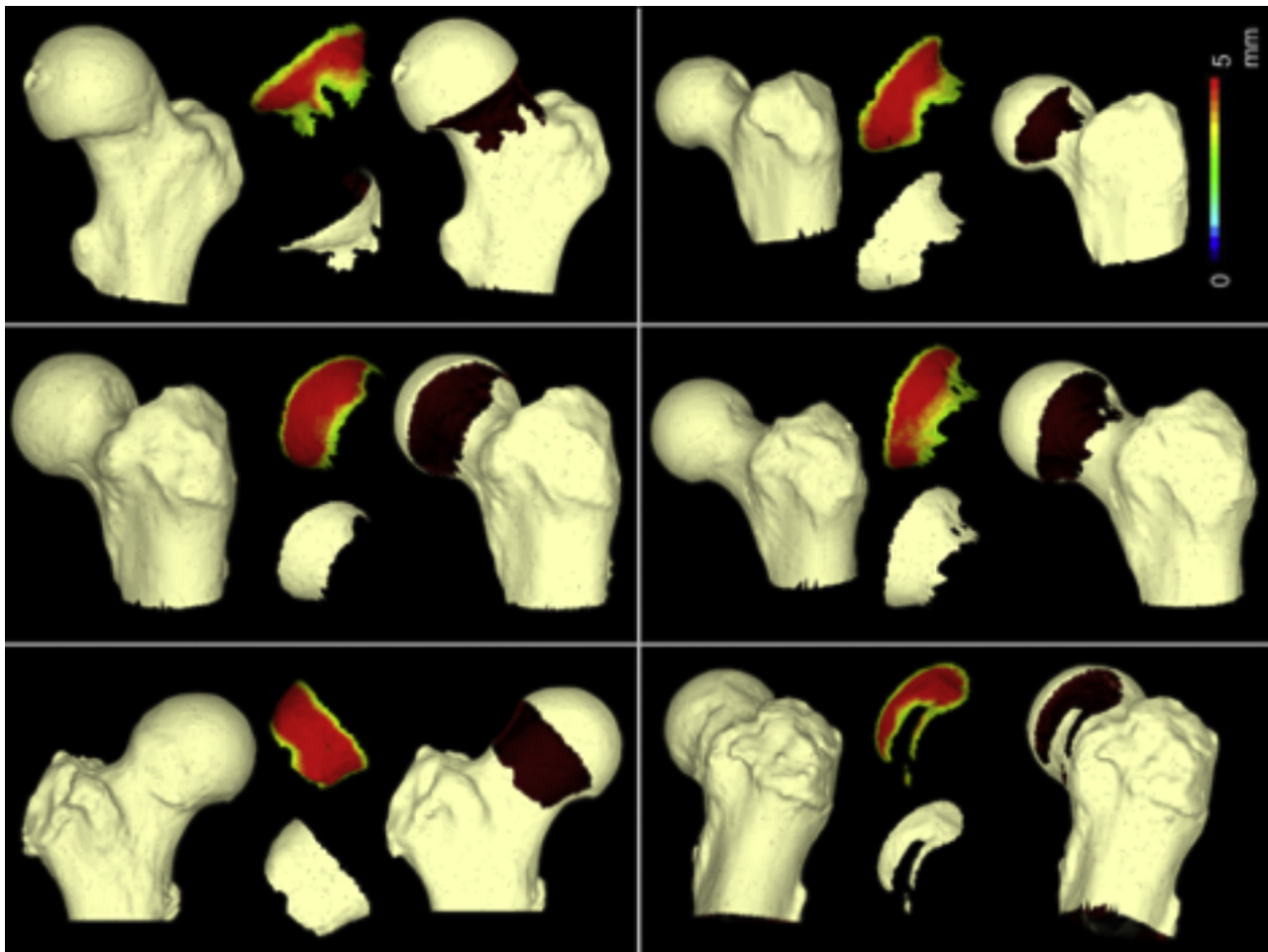


Fig 2. Preoperative and postoperative 3-dimensional–reconstructed hip models of cadaveric specimen with application of the image subtraction analysis quantifying femoral osteochondroplasty volume, femoral osteochondroplasty surface area, and femoral osteochondroplasty max and min height. A scale (top right corner) demonstrates the surface-to-surface difference measured in millimeters between preoperative and postoperative bone models with blue representing minimal resection and red indicating greater than 5 mm of resection.

$\alpha = 0.05$ using a 2-tailed analysis was used to determine statistical significance. The strength of the bivariate correlations were defined as follows: weak 0.1 to 0.3, moderate >0.3 to <0.5 , and strong as 0.5 to 1.00.²⁶ All statistical analysis was performed using SPSS (version 26; IBM, Armonk, NY).

Results

There was a significant decrease in the AA after open femoral osteochondroplasty (preoperative $61.7 \pm 6.0^\circ$ vs postoperative $38.0 \pm 5.2^\circ$; $P < .001$). The preoperative and postoperative AAs and open femoral osteochondroplasty measures are displayed in [Table 1](#). There were significant positive correlations between preoperative AAs and the osteochondroplasty measures of volume and surface area resected. No significant correlations were found between the change in AA and the osteochondroplasty variables ([Table 2](#)).

Discussion

In this study, we found that the preoperative AA measured on an oblique axial-view CT scan demonstrated strong positive correlations with amount of bone surface area and volume resected during an open femoral osteochondroplasty. These observed in vitro findings reveal an important association between what the surgeon visually defines as cam-type pathomorphology, and a common clinical imaging measure that is used to identify cam morphology in a patient with FAIS. However, in vivo studies are needed to further investigate this link using in vivo and arthroscopic femoral osteochondroplasty for cam-type morphology.

3D image evaluation of the hip in patients with FAIS could help to more clearly define a consistent definition for cam-type pathomorphology. Although our findings provide important preliminary evidence of a link between clinical measure of the preoperative AA and changes in the actual bone surface during surgery, it

Table 1. Variables of Interest

Preoperative alpha Angle, °	61.7 ± 6.0
Postoperative alpha angle, °	38.0 ± 5.2
Δ alpha angle, °	23.8 ± 7.1
FSA, mm ²	1,156.7 ± 262.8
FV, mm ³	2538.3 ± 1062.9
FH mean, mm	2.1 ± 0.4
FH max, mm	4.6 ± 0.5

NOTE. Values are mean ± standard deviation.

Δ alpha angle = change in alpha angle from preoperative to postoperative;

FH max, femoral osteochondroplasty maximum height; FH mean, femoral osteochondroplasty mean height; FSA, femoral osteochondroplasty surface area; FV, femoral osteochondroplasty volume.

was also clear from our results that considerable variability exists in cam morphologies (Fig 2). Despite using different 3D analytic methods, our findings are consistent with those of Harris et al.,²² who also reported considerable variability in the 3D shape of the proximal femur when evaluated using a statistical shape model in patients with FAIS and controls. Interestingly, this same research group also found that the AA measure on CT scans was only able to describe about one half of the variation in the actual shape of the 3D cam morphology when the statistical shape model were generated from 3D-reconstructed CT scan.²¹ Although these findings do expose the limitation of the AA's ability to comprehensively define 3D femoral cam-type morphology, the fact that our study and other authors found associations with this clinical imaging measure is promising and warrants further investigation. A better understanding of how to quantify the 3D cam-type morphology will advance the field of hip preservation by helping establish a threshold for what defines pathology. These methods can also provide unique and novel ways to comprehensively assess and understand the implications these 3D morphologies by combining both 2-dimensional (2D) and 3D-based measures.

Multiple clinical reasons exist as to why comprehensive evaluation of cam morphology is necessary for successful postoperative outcomes in patients with FAIS. One important reason is that residual cam-type morphology is the most common indication for revision hip arthroscopy secondary to continued pain and poor outcomes.⁷⁻¹⁰ Perhaps the lack of universally agreed-on pathologic preoperative threshold, as well as the appropriate postoperative thresholds, may contribute to cam morphology under-resection in patients with FAIS. A recent systematic review highlighted the variability in AA threshold recommendations with these authors concluding that an alpha angle larger than 60° should be used to classify pathologic cam morphology.¹¹ Another important clinical reason for comprehensive evaluation also is related to patient selection for surgical intervention.

Table 2. Bivariate Correlations Between Preoperative, and Alpha Angle Delta and All Femoral Osteochondroplasty Variables.

	Preoperative Alpha Angle,		Δ Alpha Angle,	
	r	P Value	r	P Value
FSA, mm	0.899	.007*	0.294	.286
FV, mm ³	0.899	.007*	0.294	.286
FH max, mm	0.600	.104	0.348	.250
FH mean, mm	0.551	.129	0.294	.286

Δ alpha angle = change in alpha angle from preoperative to postoperative.

FH max, femoral osteochondroplasty maximum height; FH mean, femoral osteochondroplasty mean height; FSA, femoral osteochondroplasty surface area; FV, femoral osteochondroplasty volume.

*Indicates statistical significance at .05.

There is clear evidence that surgical intervention for FAIS demonstrates very good-to-excellent short- to mid-term outcomes in regards of pain reduction, return to function, and patient satisfaction.^{3,4,27-31} Although clinical outcomes of long-term studies continue to show positive outcomes, the field of hip preservation must continue to strive for a better understanding of the role of the 3D morphology in the development of hip pain and symptoms to best select in patients with FAIS appropriate for surgery. Interestingly, a recent study found that a volumetric analysis of cam morphology demonstrated superior reliability to the AA measure and that these 3D measures were significantly correlated with the extent of labral tearing whereas the alpha angle was not related to the labral tear extent.¹⁹ This association between 3D morphology and associated joint injury highlights the need for a better understanding of the 3D nature of these morphologies as they relate to causing joint damage and the development of symptoms. The findings from the current study add to previous studies using 3D analysis methods and demonstrate that there is an association between the complex 3D aspects of cam morphology and the 2D measures we use to evaluate this 3D hip disorder in the clinical setting.

Limitations

As is the case with any study, a number of limitations must be considered. This was an exploratory study using 3D image-based analysis methods, therefore we used a small sample of 6 cadaveric hemipelvis specimens. These specimens also were used as part of a larger study investigating surgical cam resection. This small sample may elevate the risk of type II error. However, the sample size used in the current study was consistent with similar in vitro cadaveric studies.³²⁻³⁶ The 3D femoroplasty metrics required both preoperative and postoperative CT imaging. CT is not routinely performed postoperatively due to radiation exposure; however, previous studies have demonstrated absolute

agreement between CT and MRI proximal femoral bone models, demonstrating long term potential clinical utility.¹⁸ Hip arthroscopy has become increasingly popular over open approaches for the treatment of FAIS. Although no longer the clinic norm, the present study was performed in the open setting. Future studies a warranted in the arthroscopic setting to demonstrate the in vivo application of this technique. However, this approach allowed for direct visualization of the bony deformity and both preoperative and postoperative proximal femoral bone models can be produced in the arthroscopic setting as well. The 2D alpha angle was only measured on the oblique axial slice of the CT. Future studies should include AA measures based on commonly ordered clinical screening radiographs or 3D bone model–based radial sequence measures. In addition, we did not account for femoral head size between specimens in the osteochondroplasty analysis results. Previous studies have found that femoral head volumes were significantly larger for male than female subjects and correlated with increasing patient height.^{37,38} Theoretically, a larger femoral head should require a greater amount of bony resection per degree change in AA. Future studies may, therefore, control for femoral head volume in reporting osteochondroplasty volume as a function of the size of the femoral head.

Conclusions

In this study, pre- and postoperative 3D bone models could be used to quantify femoral osteochondroplasty and to determine whether the 3D-based metrics are related to clinical AA measures.

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