Statistical Shape Modeling to Quantify and Comparison of Proximal Femoral Cortical Bone Thickness between Patients with Femoroacetabular Impingement and Normal Hips Analyzed by Statistical Shape Modeling

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Introduction: Hip osteoarthritis (OA) develops in one out of four people over their lifetime [1]. Within the last decade, femoroacetabular impingement (FAI) has been implicated as a primary cause of hip OA in young adults [2]. Cam-type FAI is characterized by an aspherical femoral head and reduced head-neck offset, caused by a bony lesion at the head-neck junction. Cam FAI causes abnormal contact between the femur and acetabulum, especially near the bounds of hip motion, that may result in early cartilage degeneration and bone remodeling. Cam FAI is treated by resecting bone to improve head-neck offset and sphericity of the femoral head. The depth and volume of resection is crucial to patient outcome and satisfaction[3]. Inadequate resection will not restore normal range of motion, and this is noted as the primary reason for repeat surgery [4]. However, too aggressive of a resection may weaken the femoral neck, leading to an iatrogenic hip fracture [5]. As cortical bone contributes to the majority of load bearing within the hip [6], it is important to understand how cortical bone thickness is distributed throughout the femoral head in normal hips and patients with cam FAI, especially over the region of the cam lesion. The purpose of this study was to quantify and compare variation in proximal femoral head cortical bone thickness and total volume of the cortex in normal controls and patients with cam-type FAI using statistical shape modeling.

Methods: With Institutional Review Board approval, volumetric computed tomography (CT) images of the proximal femur were acquired using a Siemens SOMATOM 128 Definition CT Scanner (120 kVp tube voltage, 512 x 512 acquisition matrix, 1.0 mm slick thickness, 0.9-1.0 pitch, 250 mAs + Care-Dose tube current, 300-400 mm field of view) on 14 cam FAI patients (13 males) and 10 control subjects (5 males). The patients were diagnosed with cam FAI using standard clinical measures [7] and were scheduled for surgery. The symptomatic side was analyzed in patients, while the side was chosen randomly for control subjects. CT datasets were upsampled to improve resolution. Cortical and trabecular bone layers of each proximal femur were semi-automatically segmented and reconstructed from the CT image data using Amira (v5.4, Visage Imaging, San Diego, CA). Reconstructed surfaces of the cortical and trabecular layers of bone were used to determine the thickness of the cortical bone over the surface of the femoral head and proximal shaft above the lesser trochanter. Triangular surface meshes were created for each femur, with the cortical thickness specified at each node. The surfaces were pre-processed to improve alignment and mesh quality prior to quantifying the variation in mean shapes and corresponding cortical thicknesses for each group in ShapeWorks [7]. Correspondence points (n=2048) were automatically placed on each sample surface in ShapeWorks using a gradient descent energy function to derive the mean cam and control femur shape.
Results: The average and standard deviation age, weight and body mass index (BMI) of the patients and (controls) were 25.3±6.5 (26.4±4.3) years, 82.7±11.7 (70.0±14.0) kg, and 25.6±3.5 (23.0±3.9) kg/m², respectively. Inspection of the mean shape in each group revealed that patients with cam-type FAI had increased cortical thickness in the anterosuperior and anterolateral regions of the head-neck junction (Fig. 1), which is typically the location of cam lesion and subsequent bone resection during surgery. The maximum thickness of 3.57 mm in the head-neck junction in cam patients was significantly greater than that of the control femurs at 1.38 mm. The percent volume of cortical bone with respect to total bone volume showed an average of 18.1±4.3% in the patients and 16.2±2.4% in the controls, but the difference was not significant (p=0.121). The mean cam femur was 22.7% larger by volume in comparison to the mean control femur, while the volume of cortical bone was 41.3% greater. The cam femurs were significantly larger in total volume and volume by cortical and trabecular bone layers (p=0.038, p=0.003, p=0.084), but the differences for cortical volume as a percent of total volume were not significant (p=0.121).

Discussion: In comparison to femurs of control subjects, cortical bone thickness in patients with cam FAI is increased in the anterosuperior and anterolateral region of the femoral neck. Increased cortical bone thickness in these regions could be caused by bone remodeling in response to repetitive impingement. The larger proportion of males as well as the higher average weight and BMI in the cam FAI group could, in part, explain the difference in volume between groups, but the characteristic bump on the mean cam shape is consistent with clinical observations. The lack of statistically significant differences in normalized cortical volume suggests that the overall thickness is not increased over the proximal femur as a whole, but only in the region of the cam lesion (Fig. 1). Also, general shape variations between cam FAI and control femurs agree with prior work [7].

Significance: Understanding the geometry of the trabecular and cortical layers of bone in patients with cam-type FAI could improve pre-operative planning by providing templates to guide surgical resection. The volume and distribution of cortical bone in the proximal femur of patients with cam-type FAI is crucial to understanding the implications of resection on the forces in the femoral neck. Determination of these metrics and presentation of anatomical variation using shape modeling for a larger population may reduce the need for additional pre-operative imaging. The analysis approach used in this study could easily be extended to larger studies and other populations with hip pathology to improve our biomechanical understanding of the hip.
Figure 1. Mean cam (top) and control (bottom) shapes representing the mean cortical bone thickness for each subject cohort.