INTRODUCTION: The shape of the proximal femur is afflicted by a number of developmental disorders, including slipped capital femoral epiphysis (SCFE) and Legg-Calvé-Perthes (LCPD). SCFE hip deformities can be classified based on the severity of epiphyseal slip,1 and impingement in LCPD can be classified as cam (aspherical femoral head), pincer (acetabular overcoverage), and mixed impingement.2 While radiographs and metrics provide indices for disease diagnosis, alterations in 3-D geometry are complex and challenging to characterize and quantify.3 Statistical shape modeling (SSM) is a technique that has been used to compare sample populations by describing the variation in surface locations; the shape of an object is described in terms of parameters (modes) defined for a set of training specimens. The hypothesis of this study was that the variation in proximal femoral shape with SCFE and LCPD can be distinguished from asymptomatic normal hips by 3-D statistical shape modeling, and that statistical shape parameters are correlated with conventional parameters of proximal femoral shape.

METHODS: Experimental Design. With IRB approval, pelvic CT scans (0.625 mm slice thickness, 0.5-0.9 mm in-plane resolution) of 15 patients (age 13.2±2.6 years, range 8.8 to 16.4 years) with a range of hip symptoms and diagnoses were obtained. Left and right hips were classified, based on clinical parameters and CT assessment by a pediatric orthopaedic surgeon, as asymptomatic (n=15), LCPD Cam impingement (3), LCPD Cam+Pincer impingement (3), SCFE mild slip (5), and SCFE moderate slip (2), with others (SCFE severe slip, LCPD Pincer, 1 each) not analyzed further. Segmentation. The cortical bone surfaces of the proximal femurs were segmented from CT scans using Mimes (Materialise) by thresholding, cropping at the base of the lesser trochanter, and exporting as point clouds. Subsequent image processing was performed with custom software. Initial Alignment. Image data from right femurs were flipped to match the orientation of the left femurs, and then rigidly registered and isotropically scaled to a reference shape, defined by the largest-volume asymptomatic hip. 3-D SSM Construction. The SSM was constructed2-7 using 20 initial training shapes, 9 asymptomatic (evenly distributed from ages 8-17) and 2-3 per disease category, with principal component analysis to identify the mean shape and the modes of variation that cumulatively accounted for >90% of the variance in femur shape. Then, the SSM was applied to determine shape parameters for each femur of the study group. Conventional shape parameters. Femoral head diameter was determined as the largest diameter of a best-fit ellipsoid. Medial offset of the femoral head was determined as the shortest distance between the femoral head center and femoral shaft axis. Statistics. Correlations of scaling factor vs. age, as well as statistical vs. clinical shape parameters, were assessed by linear regression. Differences in parameters between asymptomatic and diseased hips were validated by correlation with conventional radiological parameters. SSM also demonstrated the extent of trochanter shape abnormality in LCPD and SCFE hip deformities. Mode-associated developmental deviations from asymptomatic hip shape may be due to abnormal biomechanical loads or nutritional deficiencies.

RESULTS: Proximal femoral shape was delineated by eight modes of variation. In addition to the first 4 modes (illustrated and described in Fig.1), Mode 6 described the width of the greater trochanteric region. The size and shape of proximal femurs showed expected variations. Overall size of the proximal femurs increased 3.5% per year (Fig.2A). After scaling, femoral head medial offset was most highly correlated with Mode 1 parameter (Fig.2B), and femoral head diameter with Mode 4 parameter (Fig.2C), consistent with mode illustrations. The shape of LCPD and SCFE hips differed from asymptomatic hips at characteristic sites (Fig.3), consistent with SSM Modes 1, 2, 3, and 6 (p<0.005, Fig.4). LCPD hips exhibited shape abnormality in the lateral region of the greater trochanter as well as the posterior-inferior region of the femoral head (Fig.3ABC), consistent with increased Mode 1 (Fig.4A). LCPD Cam and Cam+Pincer groups differed in A-P head sphericity and curvature of greater and lesser troCHANTERS, and were distinct in Mode 3. SCFE hips exhibited shape abnormality in the posterior-inferior femoral head (Fig.3ADE), with decreased Mode 2 (Fig.4B). SCFE severity was indicated by decreased Mode 6.

ACKNOWLEDGEMENTS: NIH, NSF.

DISCUSSION: The SSM modes delineated key variations in 3D proximal femoral shape that can occur during skeletal development, and distinguished between LCPD and SCFE. Statistical shape parameters were validated by correlation with conventional radiological parameters. SSM also demonstrated the extent of trochanter shape abnormality in LCPD and SCFE hip deformities. Mode-associated developmental deviations from asymptomatic hip shape may be due to abnormal biomechanical loads or nutritional deficiencies.

SIGNIFICANCE: Quantification of 3-D joint shape facilitates evaluation, provides insight into etiology and pathogenesis, and will be useful in management and prognosis of skeletal diseases.