Title
Defining the three-dimensional deformity in slipped capital femoral epiphysis

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Defining the Three-Dimensional Deformity in Slipped Capital Femoral Epiphysis

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Abstract

The purpose of this study was to define a novel angle measure (theta) characterizing true slipped capital femoral epiphysis (SCFE) deformity; use theta to differentiate between SCFE hips, contralateral unaffected hips, and normal hips; and to compare theta to the Southwick slip angle (SSA). 3DCT reconstructions of the pelvis and femurs were obtained and pelvic position was standardized. The center point and direction vector of the femoral epiphysis was determined. The femoral neck axis was defined. The angle between the femoral neck axis and epiphysis vector defined the 3D angle of deformity (theta). The 3D translation of the femoral epiphysis, measured as a percentage of femoral neck diameter, was measured in three planes. The average theta angle was significantly greater in SCFE hips (44.9±22.5˚) compared to control (14.5±8.8˚) or normal (14.0±6.5˚) hips ($p<0.001$). There was no significant difference in theta angle between control and normal hips ($p=0.83$). Theta angle correlated strongly with SSA ($r_s=0.774$, $p<0.001$). Its high but imperfect correlation with SSA may indicate theta as a better measure, implicating SSA as underestimating the true deformity in nearly 25% of cases.

Clinical significance: An accurate 3D measure of deformity is particularly important for surgical planning for epiphyseal reorientation. The similarity between control and normal hips may argue against the thought that there is pre-existing deformity in a pre-slip condition of unaffected contralateral hips in SCFE patients.

Keywords: SCFE; three dimensional deformity evaluation of SCFE;

Introduction

Slipped capital femoral epiphysis (SCFE) is the most common adolescent hip disorder with an incidence of approximately 10.8 cases per 100,000 children aged 8 to 15 years in the United States[14, 22, 24, 26, 46]. Although the exact etiology has not been determined, correlation has been found with obesity, race, and, more so in atypical presentations, endocrine disorders[3, 22, 29-31, 33]. The resultant deformity in SCFE has been shown to cause premature hip osteoarthritis, hip pain, decreased range of motion, impingement, and long-term disability[1, 6, 36, 43], and increasing severity of deformity increases the risk of abnormal femoroacetabular mechanics[18]. For this reason, it is crucial to classify SCFE severity accurately and use this information to guide treatment, which commonly consists of in situ pinning, reduction, or a variety of proximal femoral realignment osteotomies[4, 7, 11, 38, 44].

Although many radiographic techniques for quantifying SCFE have been utilized in the past, the most common method for assessing severity in cases of SCFE is the Southwick slip angle (SSA)[38, 41]. It is a calculation of the difference between the epiphyseal-shaft angle (ESA) of the affected hip and that of the contralateral unaffected hip on a frog lateral radiograph. A normal SSA is <12 degrees, which accounts for measurement variability[5]. Southwick graded a slip less than 30° as mild, whereas >50° is considered a severe slip[38].

However, using biplanar radiographs to diagnose SCFE has raised concerns of reliability and correlation with intraoperative findings[8, 20, 23, 35], prompting evaluation of advanced imaging to quantify the true deformity, a combination of torsion, varus, and posterior angulation through the proximal femoral physis[9, 35, 40]. Hence, new techniques have been developed, including measuring the oblique plane deformity angle (OPDA)[32] and the axial-oblique head neck angle (AOHNA)[28]. In light of the numerous historical methods of measurement employed for SCFE, it is clear that there is no obvious consensus.

Therefore, the purpose of this study was three-fold: to use 3D CT to define a novel angle measure characterizing true SCFE deformity, to use that measure for differentiating quantitatively between SCFE hips, contralateral unaffected hips in SCFE patients, and normal hips, and to compare our 3D measure with the SSA.

Methods

After receiving institutional review board approval, we retrospectively identified 58 hips from our institutional database that were treated from 2006 to 2016. Of these, 27 hips were diagnosed with SCFE, 17 hips were the unaffected contralateral hip in SCFE patients (control), and 14 hips were age- and gender-matched patients with no history of hip disease (normal). Inclusion criteria included having well-oriented AP and frog lateral radiographs, as well as availability of a pre-operative CT scan (0.625-2.5 mm thick cuts, GE LightSpeed VCT 64-slice, Piscataway, NJ). Patients who had previous treatment at an outside facility were excluded. Information such as stability according to the Loder classification[25], temporal acuity based on duration of symptoms, gender, and laterality were recorded. Southwick slip angle, oblique plane deformity angle, and axial-oblique head neck angle were measured by a single author according to standard radiographic means.

Three-dimensional CT reconstructions of the pelvis and bilateral proximal femurs were obtained with semi-automatic segmentation using Mimics (Materialise NV, Leuven, Belgium) software. The models were exported using binary stereolithography CAD format (STL) to Matlab (Mathworks, Natick, MA, USA) for analysis. Custom MATLAB software was used to standardize pelvic position by aligning the right and left anterior superior iliac spines (ASIS) in the axial plane, aligning the superior portion of the right and left iliac spines in the coronal plane, and by aligning the pubic symphysis and the anterior superior iliac spines in the sagittal plane to account for pelvic tilt and rotation, as previously described by our institution[28]. Geometric model fitting was then performed, isolating the femoral neck within the model and projecting a cylinder using least-squares regression to define the femoral neck axis. The same process was used to fit each epiphysis with a best-fit sphere to define the center point and direction vector of the femoral epiphysis (Figure 1). Once the models were established, the 3D translation of the femoral epiphysis in relation to the femoral neck was measured according to coronal, sagittal, and axial displacement oriented to the pelvis. This epiphyseal displacement (Tx, Ty, and Tz) was measured as the difference between the center point of the sphere-fit epiphysis and a point extended along the femoral neck axis to the physis and then calculated as a percentage of the femoral neck diameter (Figure 2). The degree of 3D deformity was then found by taking the angle between the femoral neck axis vector and epiphysis vector, designated as the theta angle (Figure 3). We compared these measurements to the previously described SSA angle, the oblique plane deformity angle (OPDA), and the axial-oblique head neck angle (AOHNA).

Basic descriptive statistics are reported. The Shapiro-Wilk test of normality was performed on all continuous data. Normally distributed data were analyzed with analysis of variance (ANOVA) and non-normal data were analyzed with the Kruskal-Wallis and, Mann-Whitney tests. Spearman's rho was used to evaluate correlations among continuous data. No a priori power analysis was performed. Statistical analysis was conducted using SPSS (version 12; SPSS Inc, Chicago, IL) with significance set at a p-value of <0.05.

Results

Of the 27 SCFE affected hips, three were deemed unstable and 24 stable according to the Loder classification[25]. When stratified by duration of symptoms, two were acute, five were acute on chronic, and 20 were chronic at the time of presentation. Seventeen of the SCFE hips belonged to male patients, and the remaining 10 were female. Follow-up of at least one year was documented in all cases, and only two went on to develop avascular necrosis.

Translation of the epiphysis, measured as a percentage of femoral neck diameter, varied widely between SCFE patients (Table 1). The mean posterior translation on the x-axis was 23% with a standard deviation of 19% and a range from 4% anteriorly to 66% posteriorly displaced. Mean medial translation on the y-axis was 14% (standard deviation 22%), ranging from 27% laterally to 71% medially displaced. The mean inferior translation and standard deviation on the z-axis was 30% (standard deviation 24%) with a range of 32% superior to 72% inferior displacement.

When measurements of proximal femoral epiphyseal orientation were compared between SCFE, control, and normal hips, there was a significant difference in SSA, OPDA, AOHNA, and theta angle between SCFE and control hips ($p<0.001$) indicating these measures all successfully differentiate these two conditions. The OPDA, AOHNA, and theta angle could also differentiate between SCFE and normal hips ($p<0.001$). SSA was not compared between SCFE and normal hips since frog-lateral radiographs were not consistently obtained in patients with normal hips.

The average theta angle was significantly greater in SCFE hips (44.9±22.5˚) compared to control (14.5±8.8˚) and normal (14.0±6.5˚) hips ($p<0.001$), while there was no significant difference in theta angle between control and normal hips ($p=0.83$). These statistical relationships were the same for the translational displacement measurements as well. In SCFE hips, there was no statistically significant difference among SSA (48.0±22.5˚), OPDA (54.4±18.9), AOHNA (46.6±24.2˚), or theta angle (44.9±22.5˚)($p=0.391$).

Unsurprisingly given the lack of statistically significant difference between our novel theta angle and SSA in SCFE hips, there was also strong correlation $r_s=0.774$ ($p<0.001$) (Figure 4). When comparing SCFE hip deformity as measured by theta angle and AOHNA, there was even higher correlation, $r_s=0.836$ ($p<0.001$). Slightly lower correlation was found between theta angle and OPDA, $r_s=0.723$, but this was significant as well ($p<0.001$).

Discussion

Since SCFE was first described in the literature by Paré in 1572[34], the classification and treatment scheme has continued to evolve. Appropriate treatment is determined by the temporal presentation of the SCFE (acute vs. chronic)[13], stability of the slip[25], and severity of the slip[37]. In order to determine severity using biplanar radiography, the slip magnitude must be calculated in one of three general ways: absolute displacement, percentage displacement, or angular displacement[9].

Absolute slip displacement has classically been measured by two different techniques on the anteroposterior (AP) and frog-leg lateral radiographs. The first method described by Klein et al.[19] measures the maximal epiphyseal displacement from the superior outline of the femoral neck. In an effort to enhance radiographic identification, a modification of this technique, measuring the width of the epiphysis lateral to Klein's line and comparing it to the contralateral side improves sensitivity for slip detection[15]. The second method, delineated by Mathiesen[27], records the distance from the center of the femoral head to the axis of the femoral neck. Both found the largest displacement on the lateral projection in all cases. In order to standardize displacement to the width of the femoral neck and represent the value as a percentage, Wilson[45] had previously utilized a ratio of the slip distance to the diameter of the femoral neck at the physis, defining a severe slip as greater than 50% based on these measurements. Finally, angular displacement as determined by the SSA remains the gold standard in assessment of deformity severity in SCFE.

Nonetheless, accuracy and predictability of assessing 3D deformity with single radiographic views has been questioned[9, 10]. Position-dependency and limitations by pain may interfere with obtaining frog lateral radiographs[16, 17, 39]. Thus, advanced imaging has been pursued in an attempt to characterize more thoroughly and reliably the complex deformity in SCFE hips. Cooper et al.[10] verified the reliability of the OPDA using an axial cross-sectional image (CT or MRI) and an AP x-ray of the hip, based on Paley's concept that true oblique plane deformity can only be calculated by obtaining two orthogonal views[32]. Another measurement, the head-neck angle (HNA) introduced by Weiner et al.[42] in 1978, was investigated with multiplanar CT, and it was found that the AOHNA and sagittal HNA most accurately represent maximum SCFE displacement[28].

However, despite these attempts, there is still no obvious consensus, indicating a need for the 3D measure described in this study.

The theta angle represents a novel, comprehensive 3D characterization of the true deformity in SCFE and is not limited by position dependence. Our findings of wide variability in 3D translation measurements confirm the complex deformity of SCFE in more than one plane and reinforce the importance of analyzing this condition in 3D. Although the classic deformity involves posterior and varus slipping of the epiphysis[2], some cases were found to involve anterior and valgus slips, which can only be appreciated in three dimensions, no slip being exactly the same. This is particularly important to visualize for surgical planning prior to epiphyseal reorientation procedures.

The fact that there was no significant difference between SSA, OPDA, AOHNA, and theta angle in SCFE hips confirms that the theta angle is a good measure for deformity, not deviating significantly from the traditional gold standard SSA. The utility of the theta angle is further corroborated by its ability to distinguish between SCFE hips and those in the control and normal group, which the AOHNA and OPDA were also able to do. It is not surprising that the theta angle correlated highly with the SSA (r_s=0.774), likely because the largest amount of deformity is uniplanar in a posterior direction that can usually be assessed on the frog lateral radiograph. This could account for the success of the SSA in describing severity adequately in most cases. However, the imperfect correlation implies that SSA may underestimate the true deformity described by the theta angle in nearly 25% of cases.

Furthermore, authors have previously described a pre-slip condition in which physeal changes have been found on MRI to be a precursor to a fulminant slip[2, 12, 21, 40]. Common theory is that this pre-slip condition associated with subtle deformity may be present in the “unaffected” contralateral hips of patients diagnosed with SCFE. It is this thought, along with other risk factors for SCFE such as male sex, obesity, young age, or endocrine disorders, that leads surgeons to treat the contralateral hip of SCFE patients with prophylactic percutaneous in-situ screw fixation. Our finding that there was no significant difference in theta angle between control and normal hips, however, argues against this thought that there is pre-existing deformity in a pre-slip condition of unaffected contralateral hips in SCFE patients.

As with any study, there are limitations including a relatively small sample size and short-term follow-up. Also, data analysis yielded a cohort within the SCFE patients (9 out of the 27) who had a greater than 15 degree difference between SSA and theta angle. This high variability is currently unexplained but could be related to rotation of the limb on frog lateral radiographs and pain-limited positioning. Finally, although accomplishing our goal of defining a novel 3D measure of deformity in SCFE, it is beyond the scope of this paper to evaluate the long-term outcomes of these patients in relation to this parameter. Thus, future studies should be designed to determine whether the use of the theta angle instead of the SSA would have altered treatment (in-situ pin fixation versus reduction and reorientation procedures) and whether the theta angle correlates to outcomes such as avascular necrosis. If the theta angle is adopted as the standard for true deformity in SCFE, researchers would have to reconsider previous outcome studies based on the SSA, as it may not always accurately reflect the severity of this condition.

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Legend for Figures

Figure 1: Geometric model fitting to assign femoral neck axis and femoral epiphysis vectors

Figure 2: Coordinate system for measuring epiphyseal translation

Figure 3: Theta angle defined by the angle between the femoral neck axis vector and epiphysis vector

Figure 4: Graph depicting strong correlation between theta angle and SSA

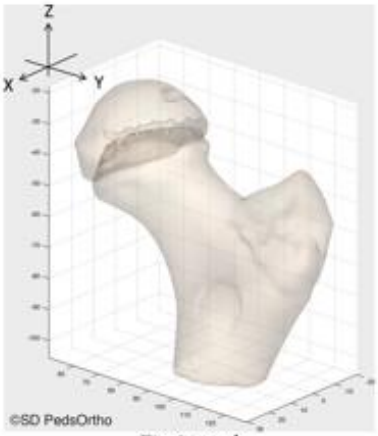

Fig 01.psd

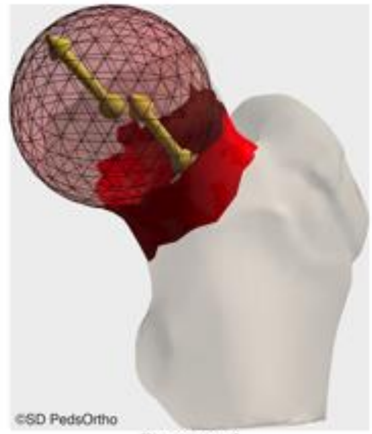

Fig 02.psd

Fig 03.psd

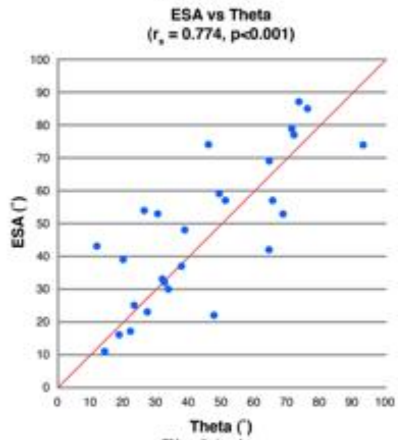

Fig 04.ai