HIP-SPINE SYNDROME: LUMBOSACRAL SPINE TRANSITIONAL VERTEBRAL ANOMALIES ARE FREQUENT IN ADULT ACETABULAR DYSPLASIA – A CROSS-SECTIONAL EVALUATION OF A PROSPECTIVE HIP REGISTRY COHORT

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ABSTRACT

HIP-SPINE SYNDROME: LUMBOSACRAL SPINE TRANSITIONAL VERTEBRAL ANOMALIES ARE FREQUENT IN ADULT ACETABULAR DYSPLASIA – A CROSS-SECTIONAL EVALUATION OF A PROSPECTIVE HIP REGISTRY COHORT

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Background: A subset of patients presenting with hip pain and instability who are found to have acetabular dysplasia (AD) do not experience resolution of symptoms after surgical management. Hip-spine syndrome is a possible underlying cause.

Objective: We hypothesized that there is increased frequency of radiographic spine anomalies in patients with AD. A secondary aim was to assess between radiographic severity of AD and frequency of spine anomalies.

Methods: This was a cross-sectional analysis of 122 hips in 122 patients who presented with hip pain and had the final diagnosis of AD. Two readers analyzed hip and spine variables using standard hip radiographic series. Frequency of lumbosacral transitional vertebra (LSTV) along with associated Castellvi grade, pars interarticularis defect, and spinal morphological measurements were recorded and correlated with radiographic severity of AD.

Results: Out of 122 patients, 110 were females and 12 were males. We analyzed 122 hip radiographic series, 59 from patients with symptoms in the left hip and 63 from patients with symptoms in the right hip. Average age at time of presentation was 34.2 ± 11.2 years. Frequency of LSTV was high (39-43%), compared to historic records from the general population, with Castellvi type 3b being the most common (60-63%). Patients with AD have increased L4 and L5 interpedicular distance (IPD) compared to published values. Frequency of pars interarticularis defect was 4%. Intraclass correlation coefficient (ICC) for hip and spine variables assessed ranged from good (0.60 – 0.75) to excellent (0.75 – 1.00). Severity of AD did not demonstrate statistically significant correlation with frequency of radiographic spine anomalies.

Conclusion: Patients with AD have increased frequency of spinal anomalies seen on standard hip radiographs. However, there exists no correlation between radiographic severity of AD and frequency of spine anomalies. In managing AD patients, clinicians should also assess spinal anomalies that are easily found on standard hip radiographs.

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CHAPTER 1: Introduction

Symptoms and clinical findings of hip pain in the young adult pose a diagnostic challenge for clinicians, as it can occur due to a variety of underlying etiologies. Acetabular dysplasia (AD) is an increasingly recognized diagnosis among skeletally mature patients presenting with hip pain and instability.[1-3] Evaluation of hip radiographs in these patients allows classification of AD, a crucial component in determining optimal surgical management[4]. The treatments for AD include hip preservation surgery or total hip arthroplasty (THA), depending upon the severity of dysplasia, arthrosis and timing of presentation.[5] Wells et al. reported that Bernese periacetabular osteotomy (PAO) is a durable alternative to THA with 15-year postoperative hip survivorship of 92%.[6] However, a subset of patients who present with hip pain secondary to AD experience incomplete resolution of pain following the procedures aimed at improving hip stability.[7,8] Hip-spine syndrome (HSS) was initially introduced by Offierski and Macnab, who demonstrated abnormal findings in both spine and hip.[9] Okuzu et al. found increased anterior pelvic tilt angles and subsequent lumbar hyperlordosis in patients with AD, suggesting increased likelihood for lumbar spondylolysis[10]. The contribution to these findings can stem from either compensatory pelvic tilt due to deficient anterior coverage or presence of spine abnormalities such as lumbosacral transitional vertebrae[11,12]. Therefore, while addressing AD, it is crucial for clinicians to view hip pain through the lens of the lumbar-pelvic-femoral complex to determine the optimal site to intervene, devise targeted course of management, maximize patient outcomes, and ultimately, minimize the economic burden to the healthcare system. We have observed that many such patients of AD, presenting with hip pain, have incidental spinal anomalies on standard hip radiographs that are used to assess AD.[13] To our current knowledge, this HSS and related anatomic findings have not been systematically studied or reported. We aimed to describe radiographic spinal anomalies in patients with AD and hypothesized that patients with AD exhibit frequent radiographic spinal anomalies on routine hip radiographs. Further, we postulated that a higher frequency of spinal anomalies would be seen in patients with more severe AD.

CHAPTER 2: Experimental Procedures

This study was a cross-sectional analysis of a prospectively collected data registry performed following all HIPAA regulations and after obtaining local Institutional Review Board approval. Informed consent was waived for retrospective evaluation.

Study Population

Initial analysis of our orthopaedic hip preservation registry, from the years 2016 – 2019 (from inception of registry to the beginning of study) identified 185 hips: 153 females, 32 males who presented to our hip preservation specialty clinic with a chief complaint of hip pain/instability and received a final diagnosis of AD. Patients who presented with pain in both hips were asked to clarify which side was more symptomatic. All patients received a standardized four view x-ray series following institutional protocol at the initial presentation, which consisted of standing anteroposterior (AP) pelvis without rotation, false profile, bilateral 45-degree Dunn, and frog lateral views.[14]

Patients who presented with clinical findings of hip pain and/or instability leading to the final diagnosis of AD met inclusion criteria. Exclusion criteria included patients with previous surgery and/or trauma to the symptomatic hip, previous spine surgery or trauma, previous medical diagnosis affecting hip or spine mobility (Ehler's Danlos, cerebral palsy), lack of sufficient radiographic imaging (absent full X-ray series as described above, AP pelvis with poor visibility L4 and L5 vertebrae, or skeletally immature as assessed via the Risser stage[15]), and a final hip or spine diagnosis excluding AD. Of the 185 qualifying hips, 122/185 (66%) were included in the study (Figure. 1: flow chart).

Clinical Data

Electronic chart review was performed, and basic demographic data was collected (age, BMI, sex), (Table. 1). All patients received a final diagnosis of AD by the senior author, a fellowship trained hip preservation surgeon. Diagnosis was based upon a combination of findings of activity related lateral hip/groin pain with insidious onset, provocative physical exam maneuvers of instability, and supportive radiographic findings of femoral head undercoverage, lateral center edge angle (LCEA) <25°, anterior center edge angle (ACEA) <20°, and Tonnis angle >10°.[3,13]

Image Analysis

Upon presentation, all patients underwent standardized full four view radiograph series of the symptomatic hip.[13] All measurements were performed on iSite (Philips, Best, Netherlands) software. Hip and spine measurements were performed by a hip preservation surgeon, and qualitative evaluation of spine anomalies was performed by two experienced musculoskeletal radiologists. In addition, the data collector was trained by an experienced musculoskeletal radiologist, and the same hip surgeon, re-measured all hip and spine quantitative variables (Table. 2) while intermittently following up with the senior readers who verified that correct measurement methods were used with random checks on multiple occasions.

On anteroposterior (AP) radiograph, the following hip variables were evaluated and measured: posterior wall sign, crossover sign, ischial spine sign, lateral center edge angle (LCEA), Tonnis angle, and femoro-epiphyseal acetabular roof (FEAR) index.[13,16,17] The false profile view was utilized to measure the anterior center edge angle (ACEA).[14] To depict the severity of AD, we used the method described by Mathaney et al. to create ordinal variables for LCEA, Tonnis angle, and ACEA measurement values by assigning mild, moderate, or severe dysplasia based upon numerical ranges.[14] For LCEA and ACEA, >15 – 25° as mild dysplasia, 5 – 15° as moderate dysplasia, and <5° as severe dysplasia. For Tonnis angle, 10 – 20° as mild dysplasia, >20 – 30° as moderate dysplasia, and >30° as severe dysplasia.[14] The same was done with FEAR index: FEAR index less than or equal to 5° was classified as stable and greater than 5° indicative was considered indicative of instability.[16] This method allows for categorization of AD severity through categorical variables, making correlation analysis with categorical spine variables possible. All hip measurements were performed on the symptomatic side.

Spine variables evaluated and measured on AP radiograph included the following: lumbosacral transitional vertebra (LSTV) and associated Castellvi grade, pubic symphysis to sacroiliac (PS-SI) index (Figure. 2a), L4/L5 transverse interpedicular distance (IPD)[18], mammillary process height (MPH), and L5 transverse process height (TPH)[14-18]. LSTV is identified on AP pelvis radiographs.[19] The Castellvi classification system (Figure. 2b) is used to grade LSTV based upon the degree of either unilateral or bilateral articulation between lumbar transverse processes and the sacrum.[20] The false profile view used for assessment of anterior femoral head coverage also provides an oblique view of the L5 vertebrae, which allows for assessment of pars interarticularis defect (Figure. 2c). Examples of all hip and spine variables assessed along with description of technique can be found in supplementary figures.

Statistics

An inter-reader agreement analysis was performed on all hip and spine variables. The intraclass correlation coefficient (ICC) was used for all continuous and ordinal variables. Cohen's Kappa was used for all nominal variables. The guidelines for interpretation of agreement coefficient are as follows: poor agreement less than 0.40, fair agreement 0.40 – 0.60, good agreement 0.60 – 0.75, excellent agreement 0.75 – 1.00.[21]

One sample t-tests were performed to compare the mean L4 and L5 interpedicular distances from our patient population to the those described by Hinck et al.[22] Spearman rank correlation was used to assess correlation between AD severity and spine variables. All correlation coefficients were tested against the hypothesis of no correlation. False discovery rate (FDR) adjusted p-values were calculated, with an adjusted $p < 0.05$ considered statistically significant. All analyses were done in R (Vienna, Austria).

CHAPTER 3: Results

Inter-Reader Agreement

All variables assessed demonstrate *Fair agreement* (Coefficient > 0.40) at minimum. Of the 16 total variables, 15 demonstrate a minimum of *Good agreement* (Coefficient > 0.60) and 14 demonstrate a minimum of *Excellent agreement* (Coefficient > 0.75) (Table 3).

Mean values for all variables measured are presented with respect to the affected hip in Table 4 and Table 5.

Frequency of LSTV and Spondylolysis

The two radiologists identified 47 (39%) and 52 (43%) hips with LSTV, respectively. These LSTV were classified using the Castellvi type classification.[23] Castellvi type 3b with bilateral fusion of the transverse process and sacrum, was the most frequent variant seen by both readers (60 and 63% frequency). The relative frequencies of Castellvi types as identified by the two readers is shown in Figure. 3.

Frequency of pars interarticularis defect on false profile radiograph was also assessed by both radiology readers and both identified the same five patients (4%) with pars interarticularis defects.

Acetabular Dysplasia and Interpedicular Distance

Mean L4 interpedicular distance (IPD) in our patient population is 29.94 ± 3.07mm (female) and 30.57 ± 3.52mm(male) while mean L5 IPD are 35.06 ± 3.02mm (female) and 35.82 ± 4.38mm (male). Comparison to L4 and L5 IPD in the general population is shown in Table. 6. Our combined patient population demonstrated statistically significant increase in L4 and L5 IPD compared to those described in the normal adult population.[22] Although there was some evidence of an increase in L4 IPD in males, the difference from the L4 IPD in the normal male adult population was not statistically significant. Given the large increase observed compared to the reference value, the small sample size of this male sub-population may have inhibited the ability to detect a statistically significant difference.

Correlation of AD Severity and Radiographic Spine Abnormalities

No statistically significant correlation between radiographic severity of acetabular dysplasia and spine morphologic measurements was observed (Supplementary Table 2) and no statistically significant correlation between ordinal acetabular dysplasia and spine variables was observed (Supplementary Table 3).

CHAPTER 4: Discussion

The management of hip pain in skeletally mature patients presenting with AD remains complex.[24] Identification of spinal anomalies using standard hip radiographs provides further understanding of the interplay between hip instability and the spinopelvic complex.

To date, there are no studies describing the frequency of LSTV identified on standard hip radiographs in AD patients. Incidental findings of LSTV on radiographs in patients without low back pain range from 4-30%.[25,26] Apazidis et al. found the majority of asymptomatic LSTV's to be Castellvi type IA. Sekharappa et al. found Castellvi type IIA to be most common in their patient population.[14,24] In our study, 39 – 43% of patients with AD were found to have LSTV, with the most common being Castellvi type IIIB. These findings indicate both increased frequency and severity of LSTV in AD patients. Increased mechanical stress in the lumbosacral spine secondary to dysplastic transverse processes is associated with extraforaminal stenosis.[27] This results in a predisposition to nerve compression which can manifest as isolated buttock pain.[28] Similarly, up to 19% of patients with AD report buttock pain upon clinical presentation.[3] The association between LSTV and low back pain, coined as Bertolotti's syndrome, remains a controversial topic in the current literature.[21] However, given high frequency of LSTV in our cohort of patients with AD, the association is intriguing and supports the validation of hip-spine syndrome.

Recent studies have demonstrated the important relationship between the spine, pelvis, and hip in AD.[12,29] AD patients, primarily those with anterior undercoverage, have lower pelvic indices, suggesting compensation through anterior pelvic tilt.[30]Through use of the PS-SI index, Daley et al. found decreased anterior pelvic tilt in patients who receive bilateral periacetabular osteotomy for AD.[12] However, our study is the first to assess correlation between severity of acetabular dysplasia and a surrogate measurement for anterior pelvic tilt (PS-SI index). While we hypothesized that increased severity of dysplasia would lead to increased compensation through anterior pelvic tilt, our statistical analysis did not reveal significant correlation. In management of AD patients, it is important to consider compensatory mechanisms which can predispose to subsequent spine pathology. Discovery of such correlations provides new insights and should be considered by clinicians managing AD patients, especially during preoperative planning.

Increased axial loading on the spine secondary to anterior pelvic tilt and subsequent hyperlordosis increases axial load on the pars interarticularis, a weak point in the vertebral column.[31] Over time, repetitive mechanical stress predisposes to the progression of spondylolisthesis.[32] Studies have identified hip OA as an independent risk factor for the development of degenerative spondylolisthesis.[33] In theory, the accelerated progression to OA in AD patients predisposes them to spondylolisthesis as well. However, to our knowledge, there have been no studies assessing the relationship between AD and frequency of pars interarticularis defect. Literature discussing detection of spondylolysis using false profile radiographs is limited. The false profile view on standard hip radiographs provides an oblique view of the L5 vertebrae, the most commonly affected vertebrae in spondylolysis, and is obtained with the same rotation as the full oblique lumbar spine view.[13,34] In our study, both radiologists independently identified L5 pars interarticularis defects in the same five patients (4%). Although our findings did not demonstrate increased frequency of pars interarticularis defects in AD patients when compared to the published range of 4 – 6% in the general population,[31] we were able to demonstrate the utility of false profile views in the evaluation of L5 pars interarticularis defects. Therefore, we recommend the utilization of false profile radiographs in AD patients to evaluate for concurrent pars interarticularis defects at L5.

IPD is readily measured on AP pelvis radiographs and can be used to support the diagnosis of various conditions. Nallamshetty et al found widening of L1-L5 IPD in patients with Marfan syndrome compared to age-matched controls[35]. Hinck et al. measured 474 spine radiographs to define the minimum and maximum tolerance ranges for normal lumbar interpedicular distances in 353 children (ages 3-5, 6-8, 9-10, 11-12, 13-14, 15-16, and 17-18) and 121 adults (>18years of age).[20] Patients who had radiographs indicative of significant anomalies or past medical history influencing growth or development were excluded from the study. Of note, Hinck et al determined that the difference in IPD between male and female was an order of magnitude less than that of age. Our combined patient population demonstrated statistically significant increase in L4 and L5 IPD compared to published values. While the exact etiology for widening of the IPD is unknown, increased IPD measurements have been correlated with increased probability for subsequent neurological deficit[36]. With this in mind, we believe IPD is a reliable and reproducible measurement that should be evaluated on AP pelvis radiographs of AD patients that may provide insight into hip-spine symptomatology. Through use of standard hip radiographs, we were able to present spine morphologic measurements (interpedicular distance of L4/L5/S1, sacral mammillary process height, and L5 transverse process height). To date, these measurements have not been described in standard hip radiographs for AD patients.

We recognize some limitations in our study. First, symptoms of back pain or functional scores, such as Oswestry disability index used for spine evaluation were not recorded in the patient charts, which would have allowed clinical correlation of spinal aberrations. We could not include all patients of AD from the cohort due to missing full hip x-ray series and other factors as shown in the Figure 1 flow chart. Our cohort was gathered from a hip registry, created at a single academic institution, which may not be representative of the general population. While the prevalence of AD, spondylolysis, and LSTV varies according to participation in specific sports[37,38], our ability to gather this information was limited by the retrospective nature of our study. This should be considered when comparing quantitative spine values and frequency of anomalies to the reported values from published studies. Future studies assessing the frequency of spine anomalies on radiographs from AD patients compared to those of non-dysplastic patients (KUB radiographs) performed at our institution could shed more light on this association while limiting population variance. The next step in uncovering the optimal management of hip-spine syndrome lies in finding a link between radiographic findings and pain location/patient reported outcome measures. A prospective study comparing post-operative outcomes in AD patients with and without incidental spine anomalies found on standard hip radiograph can increase the clinical significance of our findings. The aim of our study was to demonstrate spine anomalies on standard hip radiographs, without dedicated spinal radiographs therefore not exposing patients to further radiographic examinations. For this reason, full spine radiographs and advanced imaging were not assessed. Therefore, it is possible our patients had spine anomalies that we were unable to assess due to inadequate visualization of spine segments proximal to L5. However, performing full spine x-rays in patients with AD would subject patients to unnecessary radiation exposure and are therefore not indicated. Future studies evaluating patients with acetabular dysplasia who also have radiographs (KUB x-ray) with views of the entire lumbar spine could provide further insight into spine abnormalities otherwise unseen in standard hip radiographs.

Our study supports the utilization of standard hip radiographs in AD patients to evaluate for spino-pelvic anomalies. We observed that AD patients have increased frequency and severity of spine anomalies (increased frequency and Castellvi grade of LSTV and widening of L4/L5 IPD) when compared to published values. We believe excessive stresses due to underlying spine maldevelopment leads to alterations in hip anatomy and subsequent pathology. Our findings allow for future correlation with clinical symptoms leading to a more concrete understanding of the diagnosis and treatment of hip-spine syndrome. Comprehensive spine and hip evaluation are paramount in patients presenting with acetabular dysplasia.

TABLES

Characteristic	**Value**
Total hips (Left/Right)	122 (59/63)
Male (%)	13 (10.5%)
Female (%)	109 (89.5%)
Age [Years]	34.2 (16, 66)
BMI [kg/m^2]	26.7 (16, 40)

Table. 1: Demographics of included patients.

Variable	**Hip/spine**	**X-ray view**	**Variable type**
Posterior wall sign	Hip	AP	Nominal
Crossover sign	Hip	AP	Nominal
Ischial spine sign	Hip	AP	Nominal
LCEA	Hip	AP	Ordinal
Tonnis angle	Hip	AP	Ordinal
ACEA	Hip	False profile	Ordinal
FEAR index	Hip	AP	Continuous
Sacralization (Castellvi type)	Spine	AP	Ordinal
PS-SI index (mm)	Spine	AP	Continuous
L4 Interpedicular distance (mm)	Spine	AP	Continuous
L5 Interpedicular distance (mm)	Spine	AP	Continuous
S1 Interpedicular distance (mm)	Spine	AP	Continuous
Mammillary process height (mm)	Spine	AP	Continuous
L5 Transverse process height (mm)	Spine	AP	Continuous
Pars interarticularis defect (mm)	Spine	False profile	Nominal

Table. 2: Hip and spine variables assessed on radiographs.

Variables	**Interreader Agreement**
LCEA	0.96 (0.93, 0.97)
Tonnis angle	0.95 (0.93, 0.97)
ACEA	0.9 (0.82, 0.94)
FEAR index	0.96 (0.87, 0.99)
PS-SI index	0.96 (0.87, 0.99)
L4 Interpedicular distance	0.91 (0.74, 0.97)
L5 Interpedicular distance	0.79 (0.44, 0.93)
S1 Interpedicular distance	0.81 (0.49, 0.94)
Mammillary process height	0.88 (0.61, 0.96)
L5 Transverse process height	0.85 (0.6, 0.95)
LCEA severity	0.89 (0.83, 0.93)
Tonnis angle severity	0.84 (0.77, 0.89)
ACEA severity	0.83 (0.72, 0.89)
Posterior wall sign	0.93* (0.84, 1)
Crossover sign	0.83* (0.69, 0.97)
Ischial spine sign	0.73* (0.51, 0.95)

Table. 3: Variable agreement coefficients. Values presented are intraclass correlation coefficient. * indicates Cohen's Kappa for nominal variables

Variable	Level	All hips (%)
n		122
Posterior wall sign	Present	85 (69.7%)
	Absent	37 (30.3%)
Crossover sign	Present	23 (18.9%)
	Absent	99 (81.1%)
Ischial spine sign	Present	15 (12.3%)
	Absent	107 (87.7%)
FEAR index stability	Stable (<5°)	46 (39.7%)
	Unstable (≥5°)	70 (60.3%)
LCEA severity	Normal (>25°)	11 (9.0%)
	Mild dysplasia (>15 – 25°)	71 (58.2%)
	Moderate dysplasia (5 – 15°)	31 (25.4%)
	Severe dysplasia (<5°)	9 (7.4%)
Tonnis angle severity	Normal	33 (27.3%)
	Mild dysplasia	66 (54.5%)
	Moderate dysplasia	19 (15.7%)
	Severe dysplasia	3 (2.5%)
ACEA severity	Normal (>25°)	28 (26.7%)
	Mild dysplasia (>15 – 25°)	46 (43.8%)
	Moderate dysplasia (5 – 15°)	21 (20%)
	Severe dysplasia (<5°)	10 (9.5%)
Pars interarticularis defect	Present	5 (4.1%)
	Absent	117 (95.9%)

Table. 4: Categorical values for affected hip.

Variable (unit)	Mean Value ± StDev
n	122
LCEA (°)	16.42 ± 8.11
Tonnis angle (°)	14.07 ± 7
ACEA (°)	18.38 ± 10.37
FEAR Index (°)	6.26 ± 10.5
PS-SI index (mm)	97.92 ± 15.71
L4 IPD (mm)	29.99 ± 3.09
L5 IPD (mm)	35.12 ± 3.14
S1 IPD (mm)	39.95 ± 3.43
Right MPH (mm)	5.87 ± 3.23
Left MPH (mm)	5.73 ± 3.11
Right L5 TPH (mm)	15.4 ± 3.74
Left L5 TPH (mm)	15.81 ± 4.47

Table. 5: Hip and spine continuous variables.

	Standard Patient Mean (mm) (Hinck et al[22])	Acetabular Dysplasia Mean (mm)	Acetabular Dysplasia SD	Acetabular Dysplasia Sample Size (n)	P-value	95% Confidence Interval
L4 Interpedicular Distance						
Combined	27.00	29.99	3.09	92	< 0.001*	(29.35, 30.63)
Female	26.40	29.94	3.07	85	< 0.001*	(29.28, 30.61)
Male	27.60	30.57	3.52	7	0.067	(27.31, 33.83)
L5 Interpedicular Distance						
Combined	30.00	35.12	3.14	117	< 0.001*	(34.55, 35.70)
Female	29.00	35.06	3.02	107	< 0.001*	(34.48, 35.64)
Male	30.70	35.82	4.38	10	0.005*	(32.69, 38.95)

Table. 6: One sample t-tests of L4 and L5 interpedicular distance with reference values from Hinck et al. (1966). Unadjusted p-values are displayed. Statistically significant results after FDR adjustment are denoted with an asterisk (*). No asterisk indicates an FDR-adjusted p > 0.05.

FIGURES

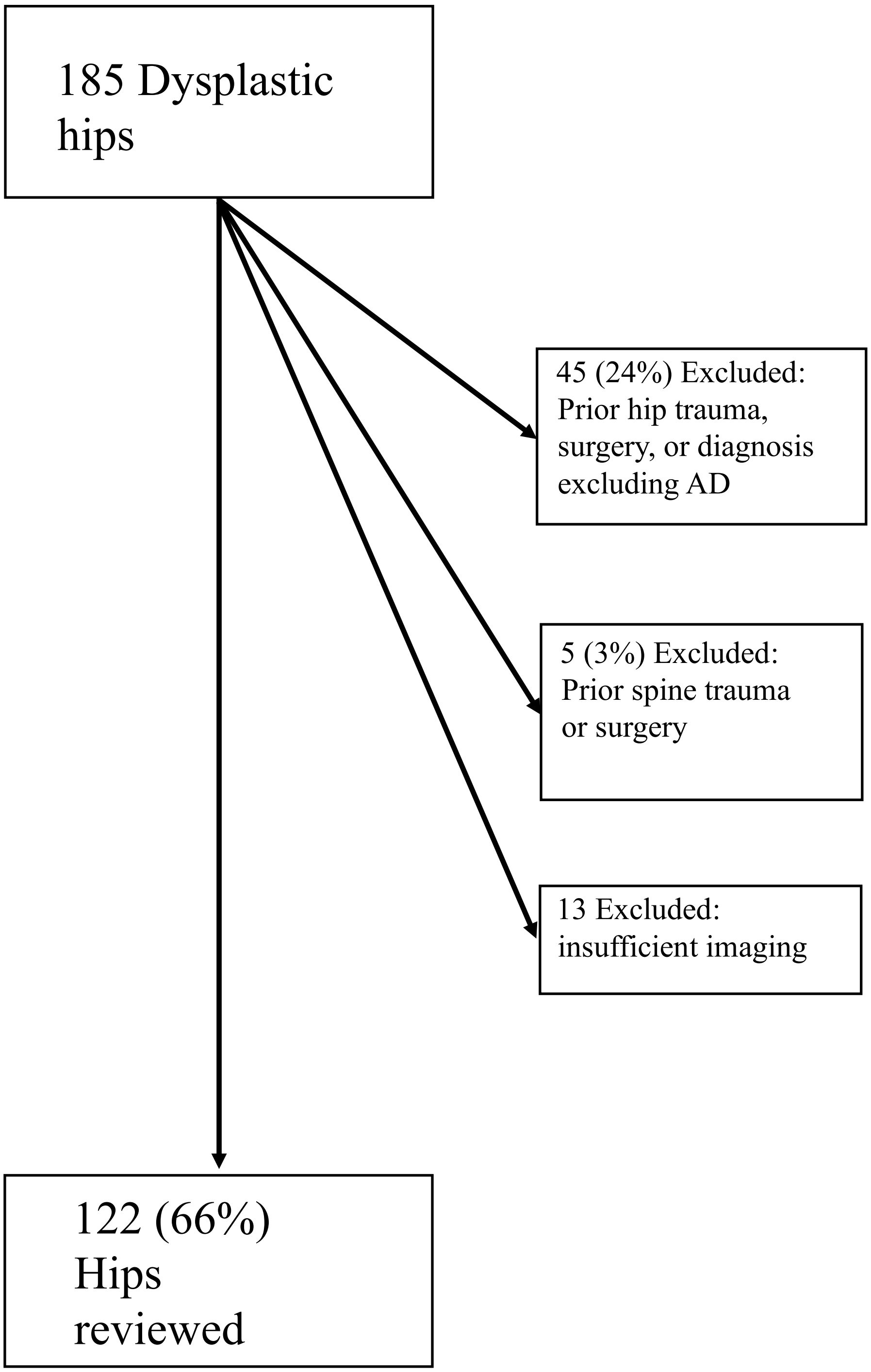


Figure. 1: Study sample following inclusion and exclusion criteria.

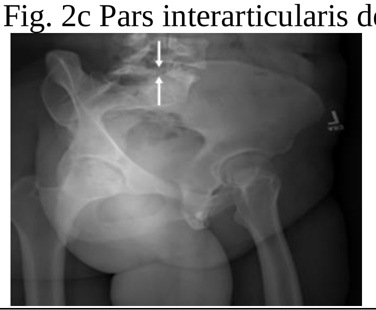
Spine Variable
Fig. 2a PS-SI index[12] 
Fig. 2b Castellvi type[39] (3b) 
Fig. 2c Pars interarticularis defect[40] 

Figure. 2: Examples of spine variables and description of technique: a) Line 1: Horizontal line connecting inferior portion of sacroiliac joints. Line 2: Drawn perpendicular and at the midpoint of line 1, extending to pubic symphysis; b) Lumbosacral transitional vertebrae identified (arrows) on left and right side, indicative of Castellvi grade 3b; c) Arrows pointing to pars interarticularis defect at the L4 level.

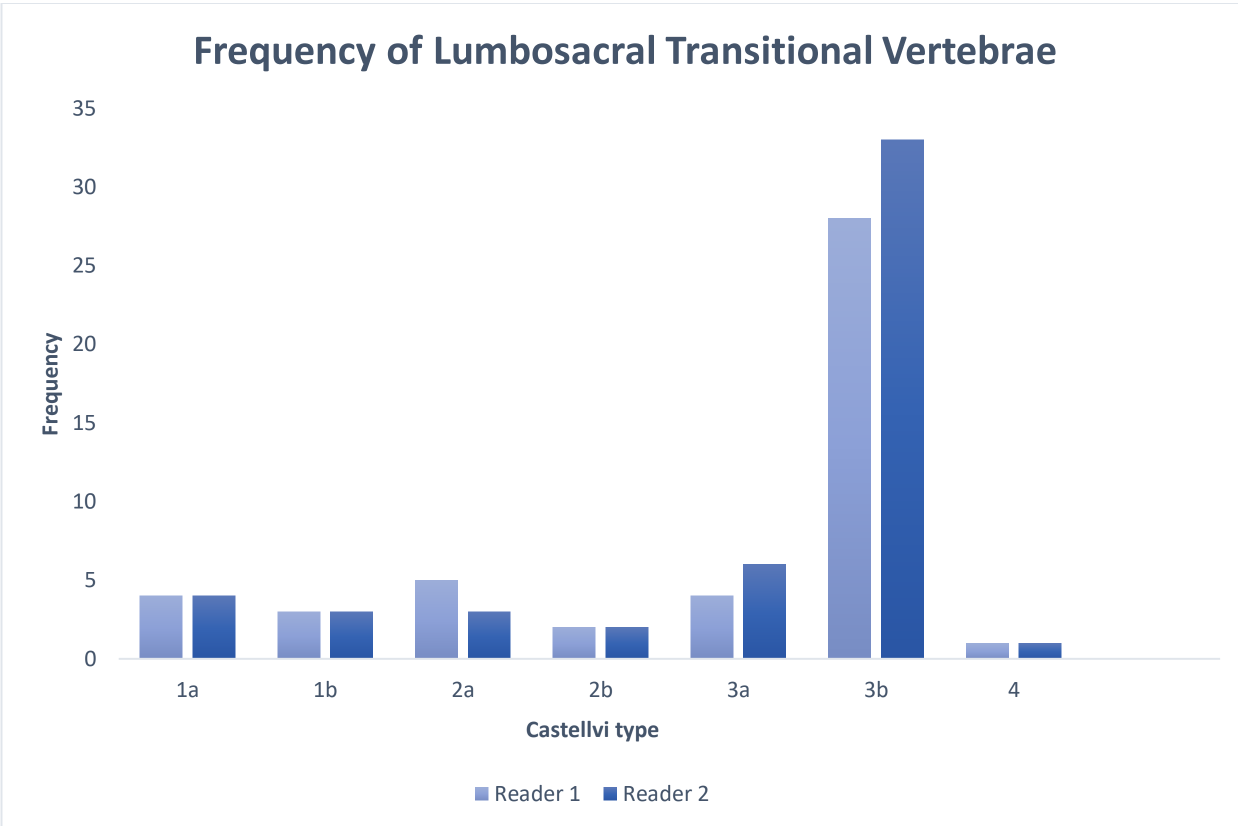


Figure. 3: Frequency of LSTV classified by Castellvi type in AD patients.

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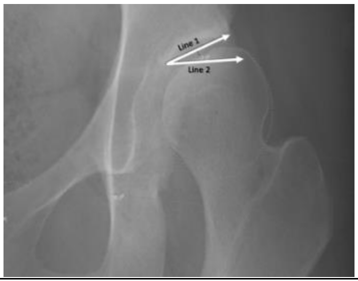
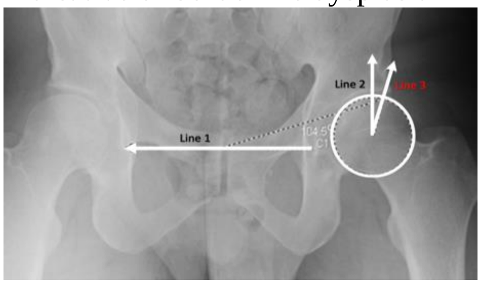
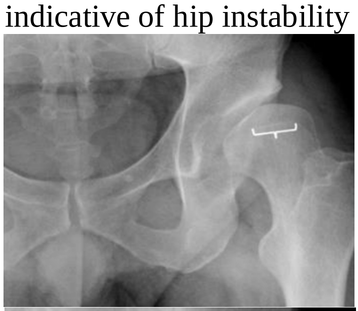
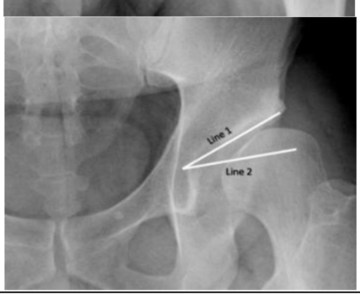
SUPPLEMENTARY FIGURES AND TABLES

Hip Variable	**Description**
AP pelvis view: Tonnis angle [13] of 18.3° indicative of dysplasia 	Line 1: Line beginning at the most inferior portion of the acetabular sourcil parallel to a line connecting the base of acetabular teardrops (not shown) Line 2: Line connecting the most inferior and superior portions of the sourcil
AP pelvis view: LCEA[13] of 24.5° indicative of borderline dysplasia 	Line 1: Line connecting acetabular teardrops (Transverse pelvic axis (TPA)) Line 2: Line perpendicular to line 1 beginning at the femoral head center Line 3: Line from femoral head center to most superolateral portion of sourcil
False profile view showing ACEA[13] of 14° indicative of moderate dysplasia 	Line 1: Vertical line from femoral head center Line 2: Line from femoral head center passing through most anterior portion of acetabular sourcil
Crossover sign[13] indicative of acetabular retroversion 	Black line (posterior acetabular rim) crosses over the white line (anterior acetabular rim) before reaching the lateral sourcil indicative of acetabular retroversion.

Ischial spine sign[41] 	Ischial spine sign is present when the ischial spine (indicated by arrowhead) is shown projecting into the pelvis, a finding that can be associated with AD and acetabular retroversion[41]
Posterior wall sign[13] 	Posterior wall sign is present when the femoral head center (dot) lies lateral to the outline of the posterior acetabular rim (outlined in white).
Acetabular depth - width ratio (ADR)[42] 	ADR is defined by the ratio (A/B) * 1000. Line A measures acetabular depth as distance measured perpendicularly from the midpoint of line B to the medial portion of the acetabulum. Line B measures acetabular width as distance between the inferior portion of the teardrop to the lateral acetabular rim. Per Laborie et al.[42], average left hip ADR in males with AD is 297.
FEAR index[16] > 5° (19.4°) indicative of hip instability  	FEAR index: Angle between line 1, through most medial to most lateral acetabular sourcil and line 2, through the middle 1/3 of the physeal scar

L5/S1 interpedicular distance[11] (IPD) 	Horizontal lines drawn between L4, L5, and S1 vertebral pedicles
Sacral mammillary process height[43](MPH) 	Mammillary body height measured as vertical distance of mammillary bodies lying superior to the sacroiliac joint.
L5 transverse process height[11] (TPH) 	Horizontal lines drawn at superior and inferior aspect of transverse process. Transverse process height (TPH) is vertical distance between the two lines.

Supplementary Table. 1: Hip and spine variable examples with description of technique.

	PS-SI index	L4 IPD	L5 IPD	S1 IPD	Right MPH	Left MPH	Right L5 TPH	Left L5 TPH
FEAR	-0.01 (-0.19, 0.17)	0.08 (-0.10, 0.25)	0.10 (-0.08, 0.27)	0.01 (-0.17, 0.19)	-0.03 (-0.21, 0.15)	-0.18 (-0.35, 0.00)	0.22 (0.05, 0.39)	0.16 (-0.02, 0.33)
LCEA	0.08 (-0.10, 0.26)	0.08 (-0.10, 0.25)	0.08 (-0.09, 0.26)	0.10 (-0.08, 0.28)	0.03 (-0.15, 0.20)	0.06 (-0.12, 0.23)	-0.09 (-0.26, 0.09)	0.02 (-0.16, 0.19)
Tonnis	-0.18 (-0.35, 0.00)	0.06 (-0.12, 0.23)	-0.10 (-0.27, 0.08)	-0.13 (-0.30, 0.05)	0.05 (-0.13, 0.23)	-0.03 (-0.21, 0.15)	0.03 (-0.15, 0.20)	-0.01 (-0.19, 0.16)
ACEA	0.02 (-0.16, 0.19)	-0.01 (-0.19, 0.16)	0.01 (-0.17, 0.18)	0.00 (-0.18, 0.18)	-0.02 (-0.20, 0.16)	0.00 (-0.18, 0.18)	-0.10 (-0.27, 0.08)	0.04 (-0.14, 0.22)

Supplementary Table. 2: Spearman correlation coefficients for continuous hip/spine variables. Correlation values that are statistically significant after FDR adjustment are denoted with an asterisk (*). No asterisk indicates an FDR-adjusted $p > 0.05$.

	Castellvi Grade
FEAR Index Severity	-0.11 (-0.28, 0.07)
LCEA Severity	0.08 (-0.10, 0.25)
Tonnis Angle Severity	0.08 (-0.10, 0.26)
ACEA Severity	0.03 (-0.15, 0.21)

Supplementary Table. 3: Spearman correlation coefficients for ordinal hip/spine variables. Correlation values that are statistically significant after FDR adjustment are denoted with an asterisk (*). No asterisk indicates an FDR-adjusted p > 0.05.

VITAE

Joshua Sun (August 22nd 1995 – present) is a fourth year medical student at the University of Texas Southwestern Medical Center. Born in Lewisville, Texas, he was raised by his grandparents in Harbin, China until he was reunited with his parents in Dallas, Texas at the age of five. He attended the University of Notre Dame in South Bend, Indiana, where he majored in Science-Business. His academic interests center on the field of orthopaedic surgery, more specifically conditions affecting the hip. In the future, Joshua plans on continuing this pursuit along with caring for patients in orthopaedic surgery residency.

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