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Original research

Assessing the Weight-Bearing Surface in Dysplastic Acetabulae: The Sourcil Index

John V. Horberg, MD [a,*], J. Ross Bailey, MD [a], Tim A. Mikesell, MD [b], R. David Graham, MD [a], D. Gordon Allan, MD [a,c]

[a] Division of Orthopaedic Surgery, Southern Illinois University School of Medicine, Springfield, IL
[b] Department of Radiology, Southern Illinois University School of Medicine, Springfield, IL
[c] Orthopaedic Center of Illinois, Springfield, IL

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ABSTRACT

Background: Although a variety of standardized measurements have been described to evaluate acetabular dysplasia, no single measurement is without limitations. We describe the Sourcil Index (SI), a novel measure of the weight-bearing surface of the acetabulum on anteroposterior pelvis films. The SI is the angle formed by the medial and lateral margins of the sourcil and the center of rotation of the femoral head.
Methods: Anteroposterior pelvis radiographs of skeletally mature patients from 2015 were reviewed. Studies with fractures or implants were excluded. Films were read by 2 orthopedic surgeons and a radiologist 3 times each, 8 weeks apart. The SI, Sharp's Angle (SA), and lateral center edge angle (LCEA) were recorded. Pearson intraclass correlation coefficients with 95% confidence intervals were calculated. The SI was then compared to the SA and LCEA to preliminarily assess diagnostic accuracy.
Results: Five hundred thirty-five hips in 292 patients met inclusion. Intraobserver reliability is as follows: SI = 0.95 (0.93-0.98), LCEA = 0.89 (0.82 -0.96), and SA = 0.90 (0.85-0.96). Interobserver reliability is as follows: SI = 0.90 (0.84-0.94), SA = 0.78 (0.64-0.86), and LCEA = 0.73 (0.56-0.82). There were 51 dysplastic hips within this cohort.
Conclusion: The SI is a reproducible measurement on plain radiographs. The SI is a two-dimensional representation of the size of the weight-bearing surface of the acetabulum and could provide an estimation of joint contact pressures. Used with existing measures, the SI may provide a more nuanced understanding of acetabular morphology.

Introduction

Developmental dysplasia of the hip (DDH) is a common, predominantly congenital derangement in hip morphology. Normal development of the hip requires a spherical, concentrically reduced femoral head within a deep, spherically concave acetabulum. Alterations in either of these factors leads to abnormal development on both sides of the joint [1–4]. Widespread screening and early intervention have led to successful treatment in infancy and adolescence of a large proportion of patients with DDH [5]. Even with successful treatment, residual dysplastic changes as well as dysplasia diagnosed in adulthood has been shown to be one of the more common underlying causes of osteoarthritis of the hip [1,2,6–8]. Some authors have implicated DDH in as many as 20%-40% of cases of end-stage coxarthrosis [9].

The acetabulae in patients with residual dysplasia are oblique and shallow with diminished femoral head coverage. The three-dimensional anatomy of the acetabulum is globally altered with insufficient depth, obliquity, and often abnormal version [3,4,10,11]. The result of this abnormal morphology is insufficient coverage and lateralization of the center of rotation of the femoral head. This decreases the surface area between the femoral head and acetabulum and concentrates the forces across the joint [1,6,7,12–14]. Increased joint contact pressures have been shown to lead to accelerated cartilaginous and labral degeneration. Ultimately, these hips develop osteoarthritis, often at a younger age than the general population [2,3,8,9].

* Corresponding author. Division of Orthopaedic Surgery, Southern Illinois University School of Medicine, P.O. Box 19679, Springfield, IL 62794-9679, USA. Tel.: +1 309-714-0980.
E-mail address: johnvhorbergmd@gmail.com

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A variety of radiographic parameters have been described to assess the relevant three-dimensional anatomy on two-dimensional imaging. No single measurement can comprehensively evaluate acetabular morphology, but several have become widely used in conjunction with one another [10]. The acetabular index as described by Sharp evaluates the obliquity of the acetabulum on anteroposterior (AP) radiographs and is defined by the angle formed between a line from the inferomedial border of the acetabulum to the superolateral border and the horizontal which is typically approximated by an interteardrop line [15]. Values greater than 40° are indicative of dysplasia (Fig. 1a). A similar measurement referred to as the acetabular index of the weight-bearing surface was described by Tönnis. The Tönnis angle is formed by the intersection of a line tangential to the medial and lateral edges of the sourcil and the horizontal. A Tönnis angle greater than 10° is considered abnormal [4,10] (Fig. 1b). The lateral center edge angle (LCEA) of Wiberg provides an assessment of the lateral coverage of the femoral head. This measurement is obtained from an AP radiograph by drawing 2 lines from the center of rotation of the femoral head; one vertical and one tangential to the lateral border of the acetabulum. An LCEA greater than 25° is normal, and less than 20° is consistent with acetabular dysplasia. The significance of values between 20° and 25° is debated, but some authors deem these hips as transitional [10,11] (Fig. 1c). The anterior center edge angle (ACEA) of Lequesne and de Seze is obtained in the same fashion as the LCEA but requires a lateral radiograph of the acetabulum often referred to as a false profile view. Similar to the LCEA, an ACEA greater than 25° is normal, and less than 20° is dysplastic [10,16] (Fig. 1d).

The Sourcil Index (SI) is a novel measurement designed to provide additional insight into acetabular morphology, the relationship between the femoral head and the weight-bearing dome, and the relative size of the contact surface across the hip joint. On AP radiographs, the angle is formed by lines extending from the center of rotation of the femoral head to the medial and lateral borders of the sourcil (Fig. 2). An SI greater than 60° is considered normal. The purpose of this study is to validate the reproducibility of the SI.

Material and methods

Patient selection

At a single medical center, a database query was performed to identify all AP pelvis radiographs obtained over the course of 1 year from January 01, 2015, to December 31, 2015. In patients with repeat imaging, all studies after the first one were excluded. Patients younger than 30 years were excluded to ensure skeletal maturity. Images were first screened to exclude studies that were not true AP projections or those with radiopaque objects obstructing visualization. All hips with ipsilateral pelvic fractures, femoral fractures, implanted hardware in the bony pelvis or femur, or evidence of prior fracture were excluded as well. Finally, Tönnis Grade III arthritic changes and hips with a radiographically indistinct sourcil were excluded as end-stage degenerative changes prevent appropriate identification of the medial aspect of the sourcil.

Figure 2. Sourcil Index (SI). Measured as the angle formed between the center of rotation of the femoral head and the medial and lateral borders of the sourcil on plain AP radiographs.

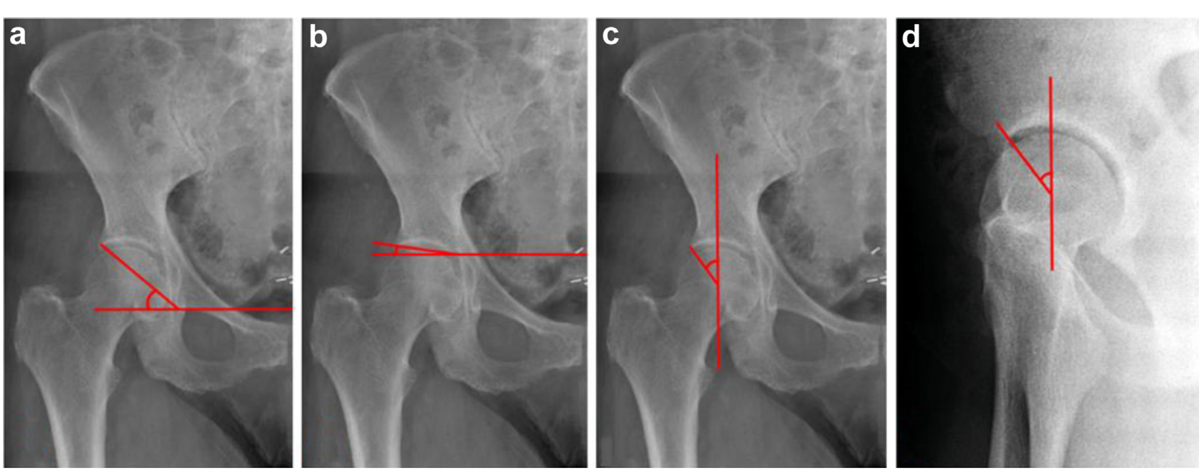

Figure 1. Selection of previously validated plain radiographic measures. (a) Acetabular Index of Sharp (SA); (b) Sourcil angle of Tönnis; (c) lateral center edge angle of Wiberg (LCEA); (d) anterior center edge angle of Lequense and de Seze (ACEA).

Measurement

All hips that met inclusion criteria were assessed individually. Patient age at the time of study and gender were recorded along with measured values for SI, LCEA, and Sharp's angle (SA). All measurements were recorded independently by 2 orthopedic surgeons as well as a radiologist. The measurements were repeated 3 times by each provider on different dates separated by 8 weeks and without access to prior recorded data.

The SI was measured from the superolateral margin of the acetabulum, excluding labral osteophytes if present, to the center of rotation of the femoral head and to the medial aspect of the sourcil. The sourcil was defined radiographically as the sclerotic superior dome of the acetabulum terminating at the apex of the cotyloid fossa (Fig. 2). The same center of rotation and superolateral point were then used to record the LCEA. The vertical line was set perpendicular to a reference line drawn between the bases of the bilateral teardrops as described by Clohisy et al. [10]. Finally, the SA was measured using the same superolateral point and points at the ipsilateral and contralateral bases of the teardrops.

Data analysis

Statistical Analysis System (SAS), version 9.4, was used for data analysis (SAS Institute, Cary, NC). Intraobserver and interobserver reliability of the SI, LCEA, and SA were determined using Pearson Intraclass Correlation Coefficient (ICC) and their 95% confidence intervals (CIs). Pearson ICCs were interpreted such that values below 0.20 were deemed poor, 0.21 to 0.4 deemed fair, 0.41-0.60 moderate, 0.61-80 good, and 0.81-1.0 excellent [17]. Acetabular dysplasia was defined by any hip with a concomitantly abnormal SA and LCEA. The lower limit of normal for the SI was found to be 60° and was determined by assessing the range of SI values in hips that were deemed nondysplastic by both LCEA and SA. The sensitivity and specificity of the SI in identifying acetabular dysplasia within this cohort were then calculated. A post-hoc power analysis was performed. The minimum sample size to determine reproducibility and to determine sensitivity and specificity was based on a sample size approximation as described by Bonett and Hajian-Tilaki, respectively [18,19].

Results

Initially, 870 hips in 435 patients older than 30 years were identified for the study. After exclusion, 535 hips in 292 patients were included (Fig. 3). Mean intraobserver reliability values of the SI (ICC = 0.95; 0.93-0.98), LCEA (ICC = 0.89; 0.82 -0.96), and SA (ICC = 0.90; 0.85-0.96) were excellent (Table 1). Interobserver reliability for the SI (ICC = 0.90; 0.84-0.94) was excellent while that for SA (ICC = 0.78; 0.64-0.86) and LCEA (ICC = 0.73; 0.56-0.82) were good. (Table 2) There were 51 dysplastic hips defined by both LCEA and SA. The average SI in dysplastic hips was 55.4 (31.3-59.8) and in non-dysplastic hips was 66.9 (60-84.4) (Fig. 6). The sensitivity of the SI was 100%, and specificity was 91%. With a target ICC of 0.8 and a 95% CI set at 0.2, the minimum sample size to assess reproducibility was estimated to be 36 hips. Based on an expected 1.0% prevalence of dysplasia and 95% CI, a minimum sample size to calculate sensitivity and specificity of 101 hips was found.

Discussion

Based on these data, the intraobserver reliability of the SI, LCEA, and SA on plain radiographs of the pelvis were all excellent. Interobserver ICCs were comparatively lower for all measures relative to their corresponding intraobserver values. This is consistent with prior validation studies which demonstrate better intraobserver than interobserver reproducibility for the LCEA and SA [20,21]. Within this group, the reproducibility of the SI remained excellent while the LCEA and SA were good. We defined dysplastic hips as any hip with a concomitantly abnormal SA and LCEA. Using this definition, the sensitivity and specificity of the SI were both excellent. The post hoc power analysis found our study to be more

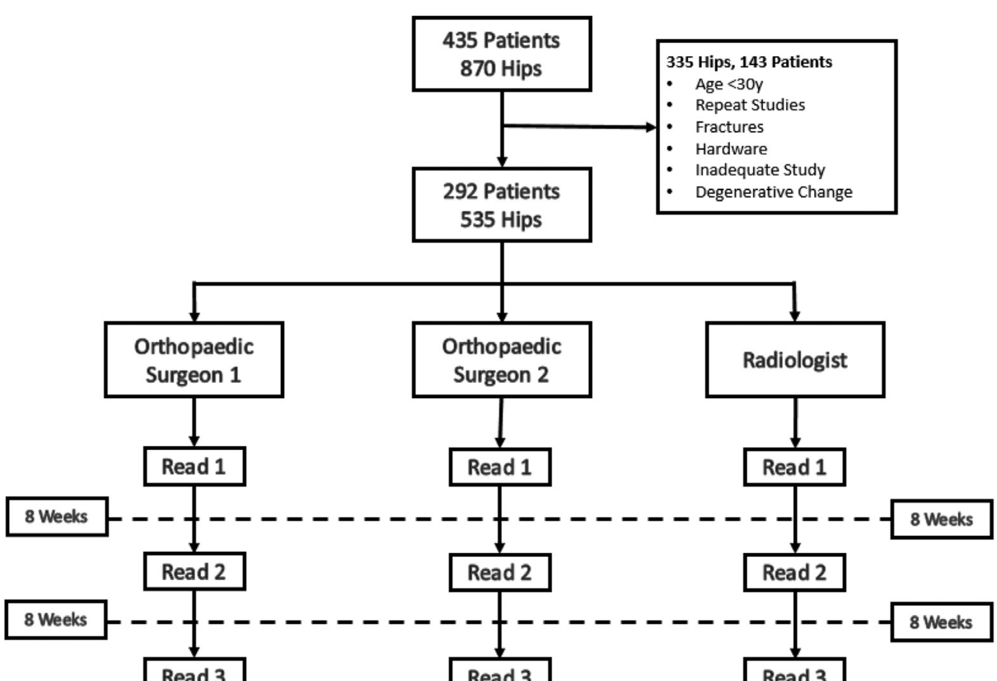

Figure 3. Summary of subject selection, exclusion criteria and sequence of data collection by each provider. All prior data blinded to providers during subsequent reads.

Table 1
Intraobserver reliability.

Intraclass correlation				
Angle	Reader			Average
	1	2	3	
SI	0.97 (0.96-0.98)	0.95 (0.94-0.96)	0.94 (0.93-0.96)	0.958 (0.93-0.98)
LCEA	0.94 (09.34-0.95)	0.87 (0.84-0.90)	0.86 (0.82-0.89)	0.892 (0.82-0.96)
SA	0.95 (0.94-0.96)	0.89 (0.86-0.92)	0.88 (0.85-0.91)	0.909 (0.85-0.96)

All measurements are continuous variables, so reliability was calculated using Pearson intraclass correlation coefficient with 95% confidence intervals. Data expressed as ICC (95% CI).

than adequately powered to validate both reproducibility and diagnostic accuracy.

Limitations of existing measurements

The ACEA and LCEA provide an estimate of, respectively, anterior and lateral femoral head coverage. These measurements rely on a vertical reference line extending from the center of rotation of the femoral head. Pelvic obliquity caused by spinal alignment, leg length inequality, or posture can falsely elevate or depress the LCEA as the pelvis rotates about the stationary vertical reference line originating from the center of femoral rotation. This mismeasurement in the LCEA can be mitigated on AP imaging by using an interteardrop line to represent the horizontal axis of the pelvis and setting the vertical reference line perpendicular to this line [10,11]. Correcting for pelvic obliquity is more challenging on false profile views making ACEA less reliable in selected patients [10,16]. In addition, the CEA provides only indirect information about the total size or orientation of the weight-bearing surface of the acetabulum.

While the acetabular indices of Tönnis and Sharp provide an adequate and reproducible estimation of the obliquity of the sourcil and acetabulum, respectively, they do not address the size of the weight-bearing surface area or the degree to which the femoral head is covered [4,15]. Furthermore, these indices do not assess the relationship between the weight-bearing surface of the acetabulum and the center of rotation of the femoral head through which the joint contact pressure is transmitted along the mechanical axis of the lower extremity.

The Sourcil Index

The SI was designed to be used in conjunction with existing measures to provide a more thorough understanding of acetabular morphology. It can be used to evaluate the size of the weight-bearing surface of the acetabulum as well as its relationship to and coverage of the articular surface of the femoral head. The orientation of the surface through which the acetabulum transmits force through the rotational center of the femoral head to the lower extremity can also be inferred (Fig. 4a-c).

Table 2
Interobserver reliability.

Interclass correlation				
Angle	Reader			Average
	1-2	1-3	2-3	
SI	0.92 (0.91-0.94)	0.91 (0.90-0.94)	0.86 (0.84-0.86)	0.904 (0.84-0.94)
LCEA	0.77 (0.73-0.82)	0.78 (0.73-0.82)	0.63 (0.56-0.70)	0.732 (0.56-0.82)
SA	0.82 (0.79-0.86)	0.82 (0.78-0.86)	0.70 (0.64-0.76)	0.786 (0.64-0.86)

All data based on first read for each observer. Data expressed as ICC (95% CI).

Biomechanical considerations

First described by Wiberg in 1939, it has become widely accepted that the characteristically shallow and obliquely oriented acetabulum found in DDH concentrates contact pressures across the hip joint leading to degeneration of articular cartilage and accelerated osteoarthrosis [2,4,8,9,11]. In 1976, Pauwel postulated that the maximum force exerted through the hip occurred during single-leg stance and that the net vector was oriented 16° off the vertical in a superomedial to inferolateral direction, passing through the medial one-third of the sourcil. This model was later challenged by Bombelli et al. who suggested that joint contact pressures were transmitted vertically through the center of the three-dimensional sourcil to the center of rotation of the femoral head [6]. In this study, they note that variations in the spheric sector of the femoral head articulating with the sourcil lead to massive changes in joint contact pressures. In fact, they found that joint contact pressures increase by 243% when the spheric sector angle alone is decreased from 90° to 56°. They further reported that increased inclination of the sourcil from the horizontal led to significantly increased contact pressures across the joint.

Subsequently, a 3D discrete element analysis by Genda et al. combined a morphologic model of the hip joint with a free body diagram of the muscular forces about the hip, with both being derived from a plain radiographic reference [12]. They demonstrated significantly increased joint contact pressures when the contact surface between the femur and sourcil was decreased. They further noted that vector of abductor pull played little role in changing joint contact forces unless the acetabulae were grossly dysplastic. Changes in the center edge angle and spheric sector angle both correlated with decreased joint contact surface area and increased joint contact pressures (Fig. 5). The increase in contact pressures associated with dysplastic acetabulae has been widely redemonstrated in computer, radiographic, synthetic, and cadaveric models [7,12–14].

Several authors have demonstrated clinically what biomechanical studies have suggested; dysplasia leads to osteoarthritis [2,3,8]. James Aronson reported that as many as 43% of all cases of end-stage osteoarthritis occur in patients with residual acetabular dysplasia [9]. Ganz et al. followed up contralateral hips in patients who had undergone unilateral THA [22]. Hips that went on to develop osteoarthritis had markedly abnormal radiographic markers for dysplasia compared with hips that did not progress to osteoarthritis [22]. A similar study was conducted by Wyles et al. in which the development of end-stage osteoarthritis in dysplastic hips was found to be 33% at 10 years and 66% at 20 years vs 20% at 10 years and 50% at 20 years in nondysplastic hips [8].

The limitations of the SI

As with any of the aforementioned measurements, the SI is not without its inherent limitations. To begin with, unlike the Tönnis and Sharp angles, the sourcil angle provides relatively little information about acetabular inclination. As the Tönnis and Sharp angles increase, the SI would theoretically decrease. However, without a reference to the inclination of the acetabulum, it is difficult to determine if this deficiency in contact surface is due a vertical or a grossly shallow but horizontal acetabulum. The SI may also be excessively and misleadingly small in patients with subluxation of the hip joint. This limitation is shared by the CEA as both measurements are referenced to the femoral head but not by the Tönnis and Sharp angles which are intrinsic to the pelvis. In this study, dysplasia was defined based on radiographic parameters which can make interpretation of the sensitivity and specificity of these radiographic measures difficult. Finally, there are

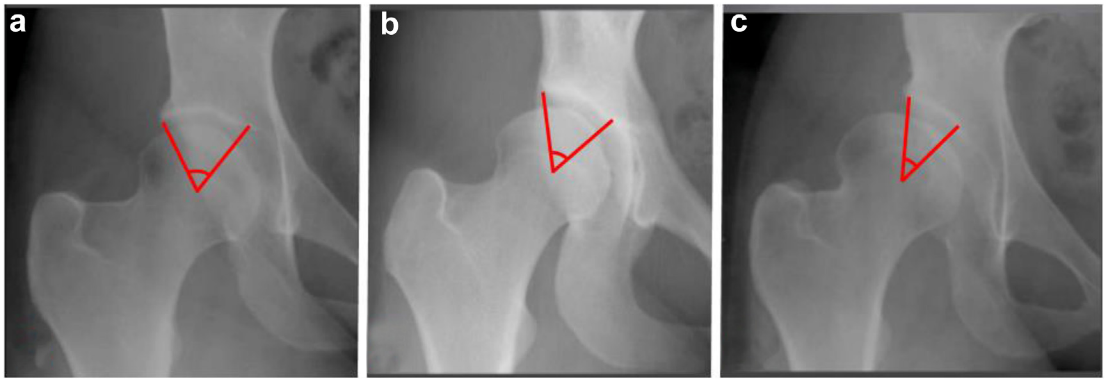

Figure 4. The Sourcil Index (SI) demonstrating decreasing size of the acetabular weight-bearing surface on (a) mild, (b) moderate, and (c) severely dysplastic hips. The orientation of the vector through which contact pressures are transmitted to the femur can be estimated as well.

well-described and validated techniques using three-dimensional imaging that can accurately measure the surface area of the sourcil and calculate joint contact pressures. In this setting, an estimation of the weight-bearing surface based on plain radiographs would be unnecessary.

Proposed utility of SI

The SI was not designed to supplant or replace any of the existing measures used to describe acetabular morphology. Rather, the SI is a tool that can be used to measure the size of the weight-bearing dome. In addition, the SI corresponds to the spheric sector of the femoral head through which forces crossing the hip are transmitted. A direct, quantitative measure of this vector can help approximate joint contact pressures across the hip.

The SI may also prove useful in planning for and following redirectional periacetabular osteotomies (PAO). An understanding of the magnitude, direction, and anatomic orientation of forces acting across the hip joint may, with further study, prove useful in predicting which patients are at the greatest risk for rapidly progressive osteoarthritis. Hipp et al. described using computer modeling to evaluate joint contact pressures in dysplastic hips before and after redirectional PAO [23]. A plain radiographic measure by which joint contact forces can be inferred would be a clinically practical way to accomplish this end. The SI may also be used, in conjunction with existing measures, to quantify improvement in the size of the effective weight-bearing surface after PAO.

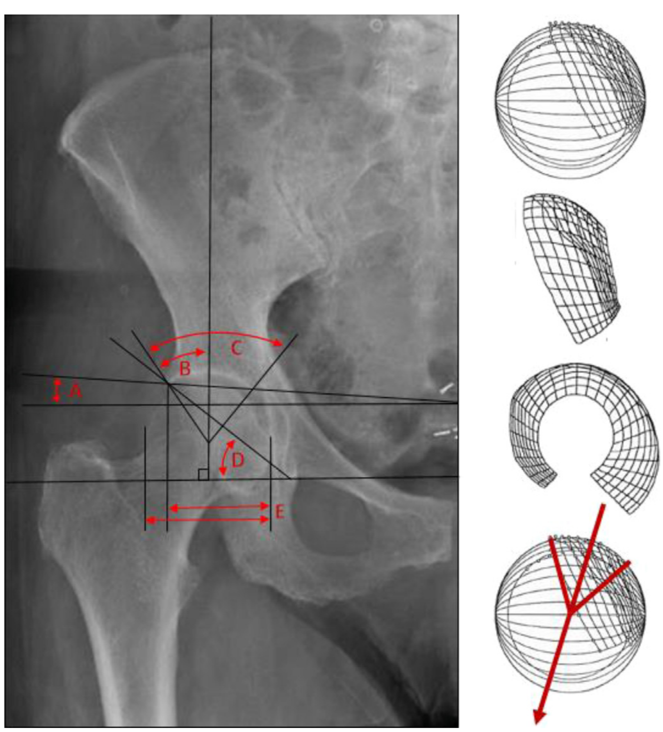

Figure 5. Assuming a spherical femoral head and acetabulum, a three-dimensional finite element model of the weight-bearing surface can be created from a plain radiograph. The orientation of the various bony landmarks defines the boundaries of the model. This can be used in conjunction with a free body analysis to calculate joint contact pressures. [a] Obliquity of the sourcil from the horizontal, clinically applied as the Tönnis angle. [b] The lateral center edge angle as defined by Wiberg. [c] Spheric sector angle representing the maximum width of the spherically concave weight-bearing surface. Represented clinically by the Sourcil Index. [d] Acetabular index of Sharp representing the inclination of the entire acetabulum from the horizontal. [e] The diameter of the femoral head relative to the lateral coverage of the acetabulum.

Limitations of this study

While our study was adequately powered, we had only 3 physicians read the images which may not be sufficient to accurately represent interobserver reliability. Furthermore, all providers used a standardized, stepwise protocol to measure each angle which

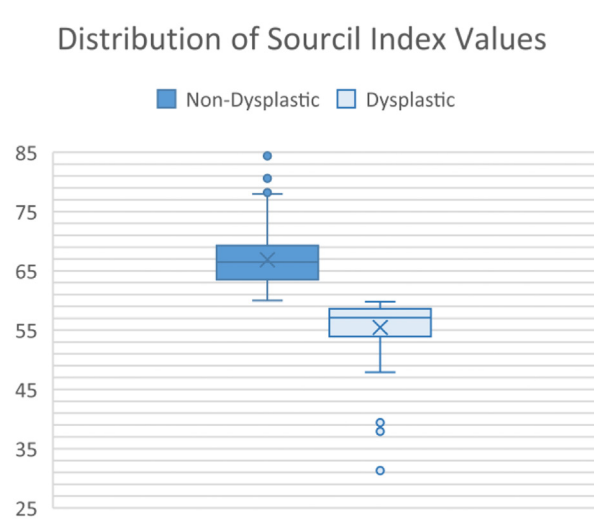

Figure 6. Distribution of Sourcil Index values for dysplastic (average, 55.4; 31.3-59.8) vs nondysplastic (average, 66.9; 60-84.4) hips.

may falsely elevate this value. To define dysplasia, we selected only 2 previously validated measures for dysplasia to include in our study. Several common measures on AP plain radiographs including the Tönnis Angle, Depth to Width Index, Femoro-Epiphyseal Acetabular Roof Index, and Acetabular Roof Angle were not assessed. Finally, although we report sensitivity and specificity for the SI from this series, these values should be validated in a separate series of radiographs. Calculating the sensitivity of the SI in the same series of images that we used to define its normal values is mathematically redundant and may artificially elevate the true sensitivity.

Conclusions

The SI is a measure of acetabular morphology on plain radiographs of the skeletally mature hip. This study has demonstrated that it is highly reproducible with excellent intraobserver and interobserver reliability. The interobserver reliability of the SI may surpass that of the SA and LCEA. Further study is needed to validate the diagnostic accuracy of the SI. Although the SI does not replace any of the previously described measures of acetabular depth or inclination, it may provide additional insight into the morphology and forces acting on the adult hip.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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