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Review article

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Systematic review of pre-operative planning modalities for correction of acetabular dysplasia

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ABSTRACT

Acetabular dysplasia, related to developmental dysplasia of the hip, causes the abnormal distribution of hip joint forces. Surgical correction of acetabular dysplasia involves repositioning the acetabulum to achieve improved coverage of the femoral head. However, ideal placement of the acetabular fragment is challenging, and has led to an increased interest in pre-operative planning modalities. In this study, we used the PubMed and EBSCO host databases to systematically review all the modalities for pre-operative planning of acetabular dysplasia proposed in the current literature. We included all case-series, English, full-text manuscripts pertaining to pre-operative planning for congenital acetabular dysplasia. Exclusion criteria included: total hip arthroplasty (THA) planning, patient population mean age >35, and double/single case studies. A total of 12 manuscripts met our criteria for a total of 186 hips. Pre-operative planning modalities described were: Amira (Thermo Fischer Scientific; Waltham, MA, USA) 12.9%, OrthoMap (Stryker Orthopaedics; Mahwah, NJ, USA) 36.5%, Amira + Biomechanical Guidance System 5.9%, Mills *et al.* method 16.1%, Klaue *et al.* method 16.1%, Armand *et al.* method 6.5%, Tsumura *et al.* method 3.8% and Morrita *et al.* method 2.2%. As a whole, there was a notable lack of prospective studies demonstrating these modalities' efficacy, with small sample sizes and lack of commercial availability diminishing their applicability. Future studies are needed to comprehensively compare computer-assisted planning with traditional radiographic assessment of ideal osteotomy orientation.

INTRODUCTION

Acetabular dysplasia, related to developmental dysplasia of the hip, causes the abnormal distribution of hip joint forces. With multiple studies showing that acetabular dysplasia can contribute to the early onset of osteoarthritis (OA) [1–3], surgical correction is commonly implemented to prevent progressive degenerative changes that might require total hip arthroplasty (THA) later in life. While various surgical methods have been proposed, such as rotational acetabular osteotomies (RAO) [4] and periacetabular osteotomies (PAO) [5], the overarching goal of correction is to return the acetabulum to normal anatomic position, and therefore improve loading conditions [6, 7].

Adequate visualization and placement of the acetabular fragment is often difficult, and therefore has contributed to the steep learning curves and high complication rates associated with these corrective procedures [8, 9]. Specifically, rates of major peri-operative complications have reached as high as 7%, with rates of reoperation being reported up to 9.7% [10–13]. Many of these reoperation procedures are due to resultant femoroacetabular impingement (FAI), a condition that has similarly been shown to contribute to OA [14]. Therefore, these negative outcomes contribute to the need for revision surgery or conversion to THA [15]. Therefore, there has been an increased need for ways of improving surgical outcomes, with focus primarily aimed at pre-operative planning of these procedures, including orientation of the acetabular fragment. Thus, the purpose of this review is to describe the modalities for pre-operative planning proposed in the literature.

MATERIALS AND METHODS

Literature search

A comprehensive literature review of the PubMed and EBSCO Host electronic databases was queried to identify all reports related to pre-operative planning of acetabular dysplasia surgical correction published between 1974 and 2019. The following MeSH terms and keywords were used with the AND or OR Boolean operators: 'preoperative, pre-op, preop, before surgery, planning, plan, operation, surgery, surgical, acetabular dysplasia, developmental dysplasia of the hip, hip dislocation and congenital'. The following inclusion criteria were used: (i) full-text manuscript must be available in English, (ii) the article must be at least a case-series pertaining to pre-operative planning, (iii) the patient population has congenital acetabular dysplasia and (iv) mean age of study population was under 35 years old. Furthermore, we used the following exclusion criteria: (i) studies related to THA planning, (ii) double or single case reports and (iii) acetabular dysplasia caused by trauma.

Data acquisition

The initial query yielded 449 publications, which were then further screened to find studies that aligned with the purpose of our review. The initial screen yielded 411 unique publications following the removal of 38 duplicates. The inclusion and exclusion criteria were then used to screen the remaining publications, which led to 44 studies being considered further. Thorough evaluation of each manuscript led to removal of 36 articles, for a total of 12 manuscripts being included for our analysis. Stepwise review of each study's reference lists was performed but did not result in any additional articles being considered for our investigation. The final analysis included 12 studies, which reported on a total of 186 hips (Table I). Preoperative planning modalities described were: Amira (Thermo Fischer Scientific, Waltham, MA, USA) (12.9% of studies), OrthoMap© (Stryker Orthopaedics, Mahwah, NJ, USA) (36.5%), Amira + Biomechanical Guidance System (Johns Hopkins University) (5.9%), Mills *et al.* method (16.1%), Klaue *et al.* method (16.1%), Armand *et al.* method (6.5%), Tsumura *et al.* method (3.8%) and Morrita *et al.* method (2.2%). The publication selection process is depicted in Fig. 1.

RESULTS

Klaue *et al.* method

Klaue *et al.* [16] was the first to present a computer-assisted model for surgical correction of 30 hips. Using an unnamed graphics program, the contours of the both the acetabulum and the femoral head were outlined from CT scans. The intersection of these contours was then used to define the coverage of the femoral head, which was then divided into four quadrants (anterolateral, anteromedial, posteromedial and posterolateral). Additionally, a 3 D reconstruction of the joint was generated to judge the morphological characteristics of the coverage in greater detail. These measurements were then used to establish optimal positioning of the acetabular fragment and the femoral head. Parameters were measured pre-operatively and at 1-year follow-up.

Pre-operative total coverage was calculated to range from 30 to 50% in the dysplastic hips [16]. Deficiency was found to be in the anterolateral (0–30%) and/or posterolateral (0–40%) quadrants [16]. The authors reported that total and local coverage of the femoral head was corrected into normal range 1-year following the procedure [16]. However, there were no statistics reported.

Armand *et al.* method

Armand *et al.* [17] built off of the preoperative plan proposed by Klaue *et al.* [16] by determining the centre of acetabular rotation using the optimization technique developed by Gill *et al.* [18] Using this centre of rotation, peak contact pressure was calculated using the algorithm proposed by Brent [19], and the lowest value was used to determine the ideal orientation. Post-operatively, the authors reviewed the results of their planned PAO through the use of the finite element model developed by Kawai and Takeuchi [20].

The biomechanical variables measured included the contact pressure, weight-bearing area and CP-ratio, a value developed to characterize the distribution of pressure across the calculated contact area. Morphological characteristics of the acetabulum measured included frontal articular cartilage angle (F-AC), frontal centre edge angle (F-CE), sagittal articular cartilage angle (S-AC) and acetabular anteversion (H-AT). Patient outcome was measured using the Harris Hip Score and the hip-rating questionnaire (q-score) developed by Johanson *et al.* [21] Median follow-up time was 2 years (range of 1.3–2.2).

Regarding patient outcomes, there was a significant improvement in the q-score following the planned PAO ($P = 0.007$) [17]. Harris Hip Score statistics were not reported. F-AC ($P < 0.001$) and F-CE ($P < 0.001$) were significantly improved at post-operative follow-up, indicating an improvement in femoral head coverage. However, S-AC ($P = 0.07$) and H-AT ($P = 0.5$) were not significantly altered by the procedure. Additionally, peak pressure ($P = 0.4$) and weight bearing area ($P = 0.3$) were not significantly improved following the procedure. Conversely, CP-ratio was found to be significantly improved following surgery ($P < 0.001$).

Amira

The Amira (Thermo Fischer Scientific, Waltham, MA) segmentation program was used by 4 studies included in our

Table I. ***Overview of studies included in our analysis***

Study	*Number of hips*	*Software used*	*Parameters measured*
Klaue *et al.* [16]	30	Author-specific method	Total coverage of femoral head
			Local coverage of femoral head
Armand *et al.* [17]	12	Author-specific method	Peak contact pressure
			Weight-bearing area
			CP-ratio
			F-AC
			F-CE
			S-AC
			H-AT
			Harris Hip Score
			q-score
Liu *et al.* [23]	10	Amira	Acetabular version
			Acetabular coverage
			Acetabular inclination
			Impingement (when ROM optimization implemented)
Liu *et al.* [24]	4		Peak contact pressure
			Peak contact areas
			Acetabular coverage
			LCEA
Liu *et al.* [25]	10		Peak contact pressure
			Peak contact area
Murphy *et al.* [22]	11[a]	Amira + Biomechanical Guidance System	Acetabular inclination
			LCEA
			Superior-anterior coverage
			H-AT
Inaba *et al.* [34]	23	OrthoMap	LCEA
			Acetabular index
			Acetabular roof obliquity
			Acetabular angle
Takao *et al.* [35]	25		ACE angle
			Acetabular roof obliquity
			Acetabular fragment thickness
			VCA angle
			Joint congruence
			Femoral head medial displacement
			Femoral head inferior displacement
Hayashi *et al.* [33]	20		Japanese Orthopedic Association Score
			UCLA Activity Score
			LCEA
			ACE angle
			Acetabular head index
			Peri-operative complications
			Accuracy of osteotomy

(continued)

Table I. (continued)

Study	*Number of hips*	*Software used*	*Parameters measured*
Tsumura *et al.* [36]	7	Author-specific method	Peak contact pressure
Millis *et al.* [38]	30	Author-specific method	LCEA ACE angle PCEA Acetabular abduction H-AT
Morita *et al.* [42]	4	Author-specific method	Horizontal and vertical distances between planned femoral head centre and centre shown on post-operative radiographs

[a]Although 12 hips were analysed with the software, only 11 had full data recorded.

F-AC, frontal articular cartilage angle; F-CE, frontal centre edge angle; S-AC, sagittal articular cartilage angle; H-AT, acetabular anteversion; LCEA, lateral centre edge angle; VCA, vertical centre anterior angle ACE, anterior centre edge; PCEA, posterior centre edge angle.

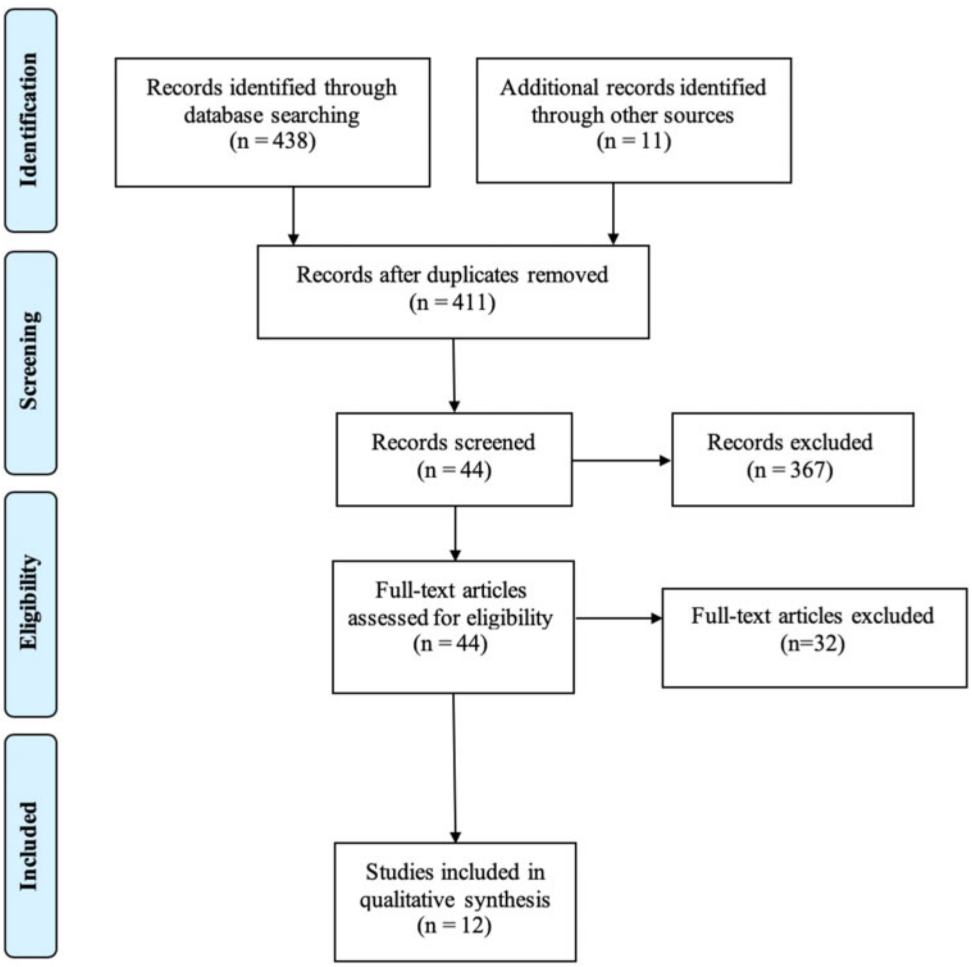

Fig. 1. Schema for Publication Selection Process Included for Final Analysis (PRISMA).

analysis, which included 35 total hips [22–25]. One of these studies [22] additionally incorporated the biomechanical guidance system (BGS) in their analysis.

Use of this software program for pre-operative surgical planning was first introduced by Liu *et al.* [23] in 2014. This novel program involves fully automatic detection of the acetabular rim from CT data. Therefore, acetabular morphology such as version, coverage and inclination could be readily calculated as the operative plan is analysed. In this initial study, the authors used this proposed modality with incorporation of impingement analysis and range-of-motion (ROM) optimization. The ROM optimization utilized a collision detection algorithm developed by Gottschalk *et al.* [26] to determine possible impingement along the motion path.

The authors first validated the automatic detection of the acetabular rim in 10 computer-assisted PAO surgeries in cadavers. They found no significant differences between computer calculated acetabular inclination (mean difference: 1.04 ± 0.95 degrees; $P = 0.69$), anteversion (mean difference: 0.6 ± 0.41 degrees; $P = 0.92$) and coverage (mean difference: 1.54 ± 1.31%; $P = 0.97$) and manually calculated morphological parameters [23]. An additional study was conducted for the same paper comparing 10 computer-assisted PAO with and without incorporation of impingement analysis and ROM optimization. Therefore, the acetabular fragment was rotated for each patient into a position that corrected morphological parameters such as inclination (normal defined between 50.7 and 66.8 degrees), anteversion (normal defined between 14 and 33.3 degrees) and lateral centre edge angle (LCEA) (normal defined as >25 degrees) with and without taking hip impingement into consideration. The authors found that the range of motion ratio, defined as the ratio of impingement-free areas in the ROM simulation, was significantly increased when the ROM optimization was incorporated compared with when it was not (71.0 ± 6.2% versus 81.9 ± 4.4%; $P < 0.05$) [23].

The Amira program was then expanded upon by Liu *et al.* in order to verify that the planning modality could improve biomechanical features of dysplastic hips [24]. After mesh generation, acetabular and femoral cartilages were modelled to be constant thickness (1.8 mm) according to the parameters used by Zou *et al.* [27] (Young's modulus $E = 15$ MPa and Poisson's ratio $\nu = 0.45$). While the Abaqus/CAE 6.10 software (Dassault Systèmes Simulia Corp, Waltham, MA, USA) was used to calculate contact constraints, frictional shear stresses were neglected due to low friction coefficients between articulating cartilages found in previous studies [28, 29]. The meshes were then validated after comparing the calculated peak contact pressures and contact areas of the reoriented hips to previous studies examining these parameters in normal hips [30, 31].

Finite element analysis was used to determine the efficacy of virtual surgery on four dysplastic hips. Following the use of reorientation planning, the authors found a significant improvement in acetabular coverage (52.6 ± 2.6% versus 62.8 ± 4.1%; $P < 0.05$) and LCEA (15.3 ± 6.0 versus 27.0 ± 1.7; $P < 0.05$) [24]. Additionally, contact area was increased from 723.5 ± 227.3 mm^2 to 1168.3 ± 320.1 mm^2 and peak contact pressure was decreased from 10.1 ± 6.1 MPa to 4.9 ± 1.1 MPa [24]. Statistics were not reported for these differences.

In a follow-up study, Liu *et al.* compared this constant-thickness cartilage model with a model using patient-specific cartilage thickness [25]. Patient-specific cartilage was calculated based on a CT arthrography protocol developed by Harris *et al.* [28]. The authors found a moderately strong correlation between the two cartilage models when examining peak contact pressures [$r = 0.634 \in (0.6, 0.8)$, $P < 0.001$] [25]. Similarly, contact areas between the two models were found to have a strong correlation ($r = 0.872 > 0.8$, $P < 0.001$) [25].

Murphy *et al.* [22] used the Amira software when examining 12 hips undergoing PAO surgeries. However, while Amira was mostly used to generate the models of the pelvis, the biomechanical guidance software was used to define the articular surface and then estimate contact pressures based on linear or non-linear discrete element analysis [32]. Similar to the parameters Liu *et al.* [23–25] extracted from their Amira-based model, the BGS can geometrically characterize the acetabulum and generate values for acetabular inclination, LCEA, superior-anterior coverage, and H-AT [32]. The BGS in this study was therefore used to collect intraoperative measurements as the surgeon performed the operation based on his conventional technique. These values were compared with those measurements made by the surgeon using K-wires. Additionally, BGS measured LCEA and acetabular index (AC) were compared with post-operative radiographic measurements taken at least 4-months after surgery.

The authors found significant differences between the BGS measured value and the surgeon's measured value for adduction angle ($P = 0.014$) and anteversion angle ($P < 0.001$) [22]. However, this difference was not found for extension angle ($P = 0.47$) [22]. Furthermore, the authors found no significant differences between the LCEA ($P = 0.68$) or AC ($P = 0.57$) when comparing BGS intraoperative and radiographic post-operative measurements [22].

OrthoMap

Three studies used OrthoMap 3 D Navigation System software (Stryker Orthopaedics, Mahwah, NJ, USA) in the pre-operative planning of surgical correction for acetabular dysplasia [33–35]. One study exclusively used the OrthoMap software for pre-operative planning [33], while the remaining two papers used additional software to aid in the final plan constructed by this program [34, 35].

Inaba *et al.* [34] examined the effects of surgical navigation with pre-operative planning on changes in LCEA, AC, acetabular roof obliquity and acetabular angle following rotational acetabular osteotomy (RAO). In addition to using OrthoMap to generate the preoperative plan, Free Form (Sensable; Wilmington, MA, USA) modelling software was used. Manual manipulation of CT data with the software allowed for the osteotomy line of acetabulum to be planned 25 mm proximal to the upper acetabular margin and from the groove of the ischium to the mid-point between the posterior acetabular margin and the greater sciatic notch. The centre of the femoral head was chosen as the centre of the hip joint. Planning aimed to rotate the acetabular fragment until the acetabular roof obliquity angle became 0 degrees. Additionally, anterior rotation was performed if acetabular coverage was deemed insufficient. The OrthoMap software was further used intra-operatively to help align the fragment based on the pre-operative plan and included warning alarms that would trigger if cuts were made past the planned osteotomy line.

There were no comparisons made between the navigation group ($n = 23$ hips) and the non-navigation group ($n = 23$ hips) directly for radiographically measured outcomes. However, both groups showed significant improvements in LCEA, acetabular head index (AHI), acetabular roof obliquity (ARO), and acetabular angle (all P-values < 0.05) following the RAO [34]. Additionally, there was no difference found between the navigation and non-navigation cohorts regarding average operative time (142 ± 34 min versus 107 ± 43 min, $P = 0.25$) and average blood loss (589 ± 377 ml versus 428 ± 281 ml, $P = 0.11$) [34]. However, there was a significant difference in fluoroscopy time between the navigation cohort (5 ± 10 s) and the non-navigated group (44 ± 21 s, $P < 0.001$) [34].

Similarly, Takao *et al.* [35] used both the planning workstation of OrthoMap along with an open source software system (Visualization Toolkit; Kitware, Clifton Park, NY, USA) to generate a pre-operative plan for RAO and to subsequently navigate the procedure with software assistance. However, unlike other studies, they did not look at the efficacy of the program, but rather looked at whether it could decrease the learning curve for RAO by comparing high-experience surgeons ($n = 16$ hips) with low-experience surgeons ($n = 9$ hips). The software itself was used to achieve an LCEA of 35 degrees and an anterior centre edge (ACE) angle of 55 degrees while maintaining femoral head coverage and adequate bony contact area. However, these measurements were all determined by the operating surgeon rather than calculated directly from the software. Outcomes measured included the ACE angle, ARO, acetabular fragment thickness, vertical centre anterior (VCA) angle, joint congruence, femoral head medial displacement and femoral head inferior displacement.

There were no differences found between the high-experience cohort and the low-experience cohort across all measured variables [35]. Specifically, there was no difference in post-operative LCEA ($P = 0.22$), ARO ($P = 0.15$), VCA ($P = 0.86$), joint congruence ($P = 0.60$), femoral head medial displacement ($P = 0.45$), femoral head inferior displacement ($P = 0.52$) and acetabular fragment thickness ($P = 0.80$) [35].

Hayashi *et al.* [33] exclusively used the OrthoMap software to examine differences in patient outcomes between surgically navigated groups ($n = 20$ hips) and non-navigated groups ($n = 17$ hips) for curved PAO. These outcomes were measured at 1-year follow-up and included the following: Japanese Orthopaedic Association (JOA) score, the University of California, Los Angeles (UCLA) activity score, LCEA, ACE angle, AHI, peri-operative complications and the accuracy of the osteotomy. In their analysis, the program was used with the goal of obtaining adequate femoral head coverage. This was defined as LCEA angle of 30 degrees and an ACE of 60 degrees. Additionally, the acetabular fragment's weight-bearing area was planned to be in a horizontal position with the centre of the hip medialized in reference to the ilioischial line.

There was no significant difference found between the cohort undergoing pre-operative planning and navigation using the OrthoMap software and the group without navigation for LCEA ($P = 0.922$), ACE ($P = 0.347$) and AHI (0.544) [33]. Similarly, there was no significant differences in JOA score ($P = 0.268$) and UCLA score ($P = 0.235$) [33]. However, while there was no differences between the two cohorts for operative time ($P = 0.283$) and blood loss ($P = 0.467$), the navigation group had a significantly lower rate of complications (0% versus 8.7%, $P < 0.001$) [33]. Additionally, mean error of the osteotomy position was smaller for the navigation group for distances of the superior pelvis (inside: $P = 0.0004$, outside: $P = 0.0478$) in the coronal plane as well as the posterior pelvis (inside: $P = 0.0192$, outside: $P = 0.0179$) in the axial plane [33].

Tsumura *et al.* method

Tsumura *et al.* [36] developed a computer software using Visual C++ (Microsoft, Redmond, WA, USA) to calculate contact force distribution for seven virtually simulated RAO. CT data was loaded into their program to generate models of the femur and pelvis, and the finite element method described by Kawai and Toi [37] was used to calculate joint pressure distribution. The centre of the femoral head and the centre of the body of the pelvis were the reference points chosen for the femur and pelvis, respectively. The peak pressures were calculated while the acetabular fragment was rotated laterally and anteriorly in increments of 5 degrees.

The ideal orientation varied between 7 hips, with transpositions involving 10–25 degrees of lateral rotation and 15–30 degrees of anterior rotation [36]. Peak pressure was decreased for all cases following the virtual osteotomy, with a mean decrease of 1.62 MPa [36]. The authors noted that for one of the cases, peak pressure was decreased over 40% [36]. There were no statistics reported by the authors.

Millis *et al.* method

The study by Millis *et al.* [38] built off of a previous study by the same authors [39] that had developed a method of calculating the bony surfaces of the hip joint based on the radiodensity of CT scans. The authors then created 3 D models by connecting the calculated contours across sequential images. This allowed for reorientation of both the acetabulum and proximal femur for pre-operative simulation of both Salter innominate [40] and dial spherical [41] osteotomies. LCEA, ACE angle, posterior centre edge angle (PCEA), acetabular abduction and H-AT were used to compare acetabular morphology in dysplastic hips with those of normal hips.

There was no significant difference found in the calculated H-AT between normal and dysplastic hips [38]. Acetabular abduction was found to be moderately increased in dysplastic hips (62 ± 6 degrees) compared with normal hips (53 ± 6 degrees) [38]. Dysplastic hips were additionally found to have a decreased average LCEA (15 degrees versus 37 degrees, $P < 0.001$), with similar decreases found for ACE angle ($P < 0.001$) and PCEA ($P < 0.001$) [38]. While both osteotomy procedures were simulated, there was no data reported on effectiveness of the pre-operative planning or on comparisons between the two procedures.

Morita et al. method

Morita *et al.* [42] was the only study to use 2 D radiographs to plan eccentric RAO. The authors proposed two plans that aimed at determining where the femoral head should be placed post-operatively, and then retrospectively compared these proposed plans with the actual surgical plan carried out. The first method involves drawing a circle on the ilium with a radius set to the same radius of curvature of the osteotome used in the procedure. A second, equally sized circle, is drawn with the centre placed at the central point of the osteotomy site (near the tear drop of the pubis). A third circle is then drawn passing through with the centre being the point where the previous circles intersect (R). This circle represents the fragment of bone to be rotated during the osteotomy. Finally, a fourth circle is drawn with R as the centre and the radius chosen as the distance from R to the pre-operative centre of the femoral head. The surgeon can then plan the centre of rotation for the acetabular fragment as well as where the post-operative femoral head centre should be located along this fourth circle. The second plan proposed by these authors was similar to the first. However, it involves drawing the circle between R and the femoral head centre first, and then drawing a circle around the proposed osteotomy segment.

The authors only compared their first method with a subjective operative plan made by the surgeon. In the four patients compared, horizontal distance between the planned femoral head centre and the centre shown on post-operative radiographs was greater for the surgeon's plan (range 3–5 mm) compared with the plan developed by the authors (range 0–1 mm). Vertical distance was similar for both methods. No statistics were reported.

DISCUSSION

Our study aimed to characterize the pre-operative planning modalities for surgical correction of acetabular dysplasia currently described in the literature. Poor outcomes after acetabular osteotomy may be due to the improper orientation of the acetabular fragment. There has been an increased need for improved surgical technique, with focus on pre-operative planning for this complex spatial surgical procedure. In our review, we found that currently proposed modalities, as a whole, are often not commercially available and have not been studied prospectively.

This study is not without limitations. Many of the studies analysed made claims regarding improvements in outcomes without reporting statistics [16, 24, 36, 42]. Additionally, sample sizes across studies, as a whole, were small and therefore may weaken the generalizability of each study's findings. Confounding variables were also not considered by the authors throughout the studies. For example, while Hayashi *et al.* [33] found decreased complication rates in their study, this could be attributed to the navigation aspect of their planning modality rather than the pre-operative plan itself. Furthermore, there was a notable lack of randomized controlled prospective studies, with most papers either failing to include control groups or virtually applying their software to CT scans of patients who already underwent surgery. Unfortunately, these limitations were unavoidable given the limited amount of literature pertaining to our study's topic. However, future studies can keep these limitations in mind to provide higher quality evidence regarding the use of these programs.

In general, providers primarily rely on conventional imaging modalities, as well as various radiological parameters that can be obtained from these techniques [43]. While the analysis of hip pathology with plain radiographs has historically yielded positive outcomes [44, 45], this modality oftentimes fails to adequately characterize pelvic tilt and rotation [46, 47]. Therefore, the utilization of magnetic resonance imaging has been viewed as a superior method of evaluating the 3 D morphology of the hip joint while allowing a more thorough consideration of labral and cartilage characteristics in the preoperative plan [48]. However, given the various complications that are still associated with correctional osteotomy procedures, more standardized imaging modalities that allow for complete 3D characterization of the hip preoperatively are needed.

While the modalities described in the present systematic review have yet to be implemented to widespread practice, multiple benefits have been demonstrated following their use. Notably, acetabular coverage of the femoral head was found to be improved when pre-operative planning modalities were implemented [16, 17, 24]. Armand *et al.* [17] reported improved frontal ACE and LCE angles following implementation of their plan ($P < 0.001$), a finding similarly found by Liu *et al.* [24] with regards to LCEA ($P < 0.05$). Regarding peak-pressure and peak-contact areas, three studies reported improvements based on their planning modalities [17, 24, 36]. Specifically, Armand *et al.* [17] found that there was an improvement in pressure distribution across contact surface following implementation of their plan ($P < 0.001$). Furthermore, these authors found that hip scores improved following their index procedure ($P = 0.007$) [17]. However, this comparison was made from pre-operative to post-operative measurements without control groups.

Apart from the methods included in our analysis, novel programs such as Hip2Norm (University of Bern, Switzerland) and Move Forward (Clinical Graphics, Zimmer Biomet) have additionally shown some promise [49, 50]. Specifically, these programs allow for hip motion and dynamics to be evaluated during the planning stage, as well as for automated detection of various radiologic parameters. This allows for both individualized planning as well as a more consistent evaluation of dysplastic hips. Similarly, the interactive aspects of these programs allow providers to fully appreciate the pathology associated with dysplastic hips when considering how to restore loading conditions. While these modalities similarly have yet to be consistently used, their development demonstrates an ongoing recognition of the limitations associated with conventional hip imaging. Therefore, until more research is conducted regarding preoperative planning for this condition, the authors recommend a combination of 2D and 3D imaging modalities in order to properly visualize the dysplastic hip.

Pre-operative planning modalities have been a recent topic of interest in order to help improve outcomes for patients being surgically treated for acetabular dysplasia. In our review, while some parameters were found to improve following use of these various modalities, there were several weaknesses in the general body of literature. Future randomized controlled studies are needed to better determine which proposed method might improve with pre-operative acetabular orientation planning. Additionally, there is a need for a more readily available software for providers to accurately and effectively apply these pre-operative plans in their respective practices, given the lack of commercially available platforms at this time.

CONFLICT OF INTEREST STATEMENT

A.F.K. reports the following disclosures: research support (Zimmer Biomet, DePuy Synthes), paid presenter or speaker (Corin, DePuy Synthes, Heraeus Medical, and Zimmer Biomet), paid consultant (Pacira Pharmaceuticals, Heraeus Medical, DePuy Synthes, and Zimmer Biomet), stock or stock options (Zimmer Biomet, Johnson & Johnson, and Procter & Gamble), IP royalties (Innomed), board or committee member (AAOS and AAHKS), and editorial or governing board (BMC Musculoskeletal Disorders). A.J.A., B.M., and L.T.S. have nothing to disclose.

REFERENCES

1. Aronson J. Osteoarthritis of the young adult hip: etiology and treatment. *Instr Course Lect* 1986; **35**: 119–28.
2. Jacobsen S, Sonne-Holm S. Hip dysplasia: a significant risk factor for the development of hip osteoarthritis. A cross-sectional survey. *Rheumatology* 2005; **44**: 211–8.
3. Cooperman DR, Wallensten R, Stulberg SD. Acetabular dysplasia in the adult. *Clin Orthop Relat Res* 1983; **175**: 79–85.
4. Ninomiya S, Tagawa H. Rotational acetabular osteotomy for the dysplastic hip. *J Bone Joint Surg Am* 1984; **66**: 430–6.
5. Ganz R, Klaue K, Vinh TS *et al.* A new periacetabular osteotomy for the treatment of hip dysplasias. Technique and preliminary results. *Clin Orthop Relat Res* 1988; **232**: 26–36.

6. Kamath AF. Bernese periacetabular osteotomy for hip dysplasia: surgical technique and indications. *World J Orthop* 2016; **7**: 280–6.
7. Leunig M, Siebenrock KA, Ganz R. Rationale of periacetabular osteotomy and background work. *Instr Course Lect* 2001; **50**: 229–38.
8. Novais EN, Carry PM, Kestel LA *et al*. Does surgeon experience impact the risk of complications after Bernese periacetabular osteotomy? *Clin Orthop Relat Res* 2017; **475**: 1110–7.
9. Zaltz I, Baca G, Kim Y-J *et al*. Complications associated with the periacetabular osteotomy. *J Bone Joint Surgery Am* 2014; **96**: 1967–74.
10. Sabbag CM, Nepple JJ, Pascual-Garrido C *et al*. The addition of hip arthroscopy to periacetabular osteotomy does not increase complication rates: a prospective case series. *Am J Sports Med* 2019; **47**: 543–51.
11. Zaltz I, Baca G, Kim Y-J *et al*. Complications associated with the periacetabular osteotomy: a prospective multicenter study. *J Bone Joint Surg Am* 2014; **96**: 1967–74.
12. Thanacharoenpanich S, Boyle MJ, Murphy RF *et al*. Periacetabular osteotomy for developmental hip dysplasia with labral tears: is arthrotomy or arthroscopy required? *J Hip Preserv Surg* 2018; **5**: 23–33.
13. Clohisy JC, Ackerman J, Baca G *et al*. Patient-reported outcomes of periacetabular osteotomy from the prospective ANCHOR cohort study. *J Bone Joint Surg Am* 2017; **99**: 33–41.
14. Ganz R, Parvizi J, Beck M *et al*. Femoroacetabular impingement: a cause for osteoarthritis of the hip. *Clin Orthop Relat Res* 2003; **417**: 112–20.
15. Hartig-Andreasen C, Troelsen A, Thillemann TM *et al*. What factors predict failure 4 to 12 years after periacetabular osteotomy? *Clin Orthop Relat Res* 2012; **470**: 2978–87.
16. Klaue K, Wallin A, Ganz R. CT evaluation of coverage and congruency of the hip prior to osteotomy. *Clin Orthop Relat Res* 1988; **232**: 15–25.
17. Armand M, Lepistö J, Tallroth K *et al*. Outcome of periacetabular osteotomy: joint contact pressure calculation using standing AP radiographs, 12 patients followed for average 2 years. *Acta Orthop* 2005; **76**: 303–13.
18. Gill P, Murray W, Wright M. *Numerical Linear Algebra and Optimization*. Redwood City, CA: Addison-Wesley, 1991.
19. Brent RP, Richard P. *Algorithms for Minimization without Derivatives*. Mineola, New York: Dover Publications, 2002. https://books.google.com/books/about/Algorithms_for_Minimization_Without_Deri.html? id=6Ay2biHG-GEC. Accessed: 2 May 2019.
20. Kawai T, Takeuchi N. New discrete models and their application to mechanics of granular materials. *Stud Appl Mech* 1983; **7**: 151–72.
21. Johanson NA, Charlson ME, Szatrowski TP, Ranawat CS. A self-administered hip-rating questionnaire for the assessment of outcome after total hip replacement. *J Bone Joint Surg Am* 1992; **74**: 587–97.
22. Murphy RJ, Armiger RS, Lepistö J *et al*. Clinical evaluation of a biomechanical guidance system for periacetabular osteotomy. *J Orthop Surg Res* 2016; **11**: 1–8.
23. Liu L, Ecker T, Schumann S *et al*. Computer assisted planning and navigation of periacetabular osteotomy with range of motion optimization. *Med Image Comput Interv* 2014; **8674**: 643–50.
24. Liu L, Ecker T, Xie L *et al*. Biomechanical validation of computer assisted planning of periacetabular osteotomy: a preliminary study based on finite element analysis. *Med Eng Phys* 2015; **37**: 1169–73.
25. Liu L, Ecker TM, Schumann S *et al*. Evaluation of constant thickness cartilage models vs. patient specific cartilage models for an optimized computer-assisted planning of periacetabular osteotomy. *PLoS One* 2016; **11**: e0146452.
26. Gottschalk S, Lin M, Manocha D. OBBTree: a hierarchical structure for rapid interference detection. In: *Proceedings of the 23rd Annual Conference on Computer Graphics and Interactive Techniques*. New York, NY: ACM, 1997.
27. Zou Z, Chávez-Arreola A, Mandal P *et al*. Optimization of the position of the acetabulum in a ganz periacetabular osteotomy by finite element analysis. *J Orthop Res* 2013; **31**: 472–9.
28. Harris MD, Anderson AE, Henak CR *et al*. Finite element prediction of cartilage contact stresses in normal human hips. *J Orthop Res* 2012; **30**: 1133–9.
29. Caligaris M, Ateshian GA. Effects of sustained interstitial fluid pressurization under migrating contact area, and boundary lubrication by synovial fluid, on cartilage friction. *Osteoarthr Cartil* 2008; **16**: 1220–7.
30. Brown TD, Shaw DT. In vitro contact stress distributions in the natural human hip. *J Biomech* 1983; **16**: 373–84.
31. Adams D, Swanson SA. Direct measurement of local pressures in the cadaveric human hip joint during simulated level walking. *Ann Rheum Dis* 1985; **44**: 658–66.
32. Murphy RJ, Armiger RS, Lepistö J *et al*. Development of a biomechanical guidance system for periacetabular osteotomy. *Int J Comput Assist Radiol Surg* 2015; **10**: 497–508.
33. Hayashi S, Hashimoto S, Matsumoto T *et al*. Computer-assisted surgery prevents complications during peri-acetabular osteotomy. *Int Orthop* 2018; **42**: 2555–61.
34. Inaba Y, Kobayashi N, Ike H *et al*. Computer-assisted rotational acetabular osteotomy for patients with acetabular dysplasia. *Clin Orthop Surg* 2016; **8**: 99–105.
35. Takao M, Nishii T, Sakai T *et al*. Comparison of rotational acetabular osteotomy performed with navigation by surgeons with different levels of experience of osteotomies. *Int J Comput Assist Radiol Surg* 2017; **12**: 841–53.
36. Tsumura H, Kaku N, Ikeda S *et al*. A computer simulation of rotational acetabular osteotomy for dysplastic hip joint: does the optimal transposition of the acetabular fragment exist? *J Orthop Sci* 2005; **10**: 145–51.
37. Kawai T, Toi Y. A new element in discrete analysis of plane strain problems. *Seisan Kenkyu* 1977; **29**: 204–7.
38. Millis MB, Murphy SB. Use of computed tomographic reconstruction in planning osteotomies of the hip. *Clin Orthop Relat Res* 1992; **274**: 154–9.
39. Murphy SB, Kijewski PK, Millis MB, Harless A. Acetabular dysplasia in the adolescent and young adult. *Clin Orthop Relat Res* 1990; **261**: 214–23.
40. Salter RB. Innominate osteotomy in the treatment of congenital dislocation and subluxation of the hip. *J Bone Joint Surg Br* 1961; **43-B**: 518–39.
41. Wagner H. *Experiences with Spherical Acetabular Osteotomy for the Correction of the Dysplastic Acetabulum* (131–45). Berlin, Heidelberg: Springer, 1978. doi: 10.1007/978-3-642-66737-4_7
42. Morita Y, Otsuru T, Munakata Y *et al*. Preoperative planning for eccentric rotational acetabular osteotomy. *Japanese J Joint Dis* 2014; **33**: 427–35.

43. Albers CE, Rogers P, Wambeek N *et al*. Preoperative planning for redirective, periacetabular osteotomies. *J Hip Preserv Surg* 2017; **4**: 276–88.
44. Clohisy JC, Carlisle JC, Beaulé PE *et al*. A systematic approach to the plain radiographic evaluation of the young adult hip. *J Bone Joint Surg Am* 2008; **90**: 47–66.
45. Lerch TD, Steppacher SD, Liechti EF *et al*. One-third of hips after periacetabular osteotomy survive 30 years with good clinical results, no progression of arthritis, or conversion to THA. *Clin Orthop Relat Res* 2017; **475**: 1154–68.
46. Tannast M, Fritsch S, Zheng G *et al*. Which radiographic hip parameters do not have to be corrected for pelvic rotation and tilt? *Clin Orthop Relat Res* 2015; **473**: 1255–66.
47. Tannast M, Zheng G, Anderegg C *et al*. Tilt and rotation correction of acetabular version on pelvic radiographs. *Clin Orthop Relat Res* 2005; **438**: 182–90.
48. Sankar WN, Beaulé PE, Clohisy JC *et al*. Labral morphologic characteristics in patients with symptomatic acetabular dysplasia. *Am J Sports Med* 2015; **43**: 2152–6.
49. Tannast M, Mistry S, Steppacher SD *et al*. Radiographic analysis of femoroacetabular impingement with hip2norm-reliable and validated. *J Orthop Res* 2008; **26**: 1199–205.
50. Van Houcke J, Khanduja V, Nakano N *et al*. Accuracy of navigated cam resection in femoroacetabular impingement: a randomised controlled trial. *Int J Med Robot Comput Assist Surg* 2017; **13**: e1839.