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Planning Acetabular Redirection Osteotomies Based on Joint Contact Pressures

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Acetabular redirection osteotomy can be used to relieve pain, improve function, and extend the life of dysplastic hip joints. To understand better the factors that may determine the acetabular reorientation that minimizes pressures, joint contact pressures were calculated by computer assisted methods in 70 dysplastic and 12 normal hips (82 patients). Calculated pressures were consistent with pressures estimated and measured by other investigators. Contact areas were 26% smaller, and contact pressures were 23% higher, in the dysplastic hips compared with the normal hips. When the acetabula were reoriented to minimize contact pressures for an activity such as the midstance phase of gait, then contact pressures were elevated for dissimilar activities such as stair ascent. Contact pressures in the dysplastic hips were reduced when the acetabula were rotated in the frontal plane to increase lateral coverage or rotated in the sagittal plane to increase anterior coverage. In most of the dysplastic hips, contact pressures were reduced twice as much when the acetabulum was rotated in the frontal and the sagittal planes. Computer assisted methods to quantify joint contact pressures can be used to assess potential candidates for reconstruction, plan acetabular redirection surgery, and possibly may improve the long term success of acetabular redirection osteotomy.

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Acetabular redirection osteotomies are used to treat patients diagnosed with painful, dysplastic hip joints.[29,30] There are two accepted theoretical goals of acetabular osteotomies in the treatment of hip dysplasia; reorient the acetabulum so pressures are better distributed over the available cartilage surface, and reorient the acetabulum to contain the femur and prevent subluxation. These goals are based on the unproven hypothesis that reducing contact pressure on cartilage will slow or prevent additional joint degeneration.

Many different acetabular osteotomies have been proposed.[1,7,8,29,32,35,36,38–40] All of these osteotomies are based on the theory that proper acetabular positioning reduces joint contact pressures and stabilizes the hip joint.[29] Clinical results with these osteotomies show approximately 80% good to excellent 7 to 15 year results,[6,21,23,37] although success rates as low as 21% can be calculated depending on the criteria used to determine success and the type of osteotomy performed.[27] Many factors may contribute to failure of acetabular osteotomies, including acetabular positioning and the presence of preexisting arthritis.

Success rates may be associated with how the acetabulum was reoriented, and some acetabular osteotomies may achieve a better acetabular reorientation than others. Acetabular osteotomies can be used to increase lateral coverage, anterior coverage, or any combinations of anterior and lateral coverage. In addition, acetabular osteotomies can medialize the socket. Surgeons can select different osteotomies based on experience and preferences for surgical approach, but a quantitative basis for intraoperative positioning of the acetabulum is defined poorly. It also is yet to be shown that the long term results of acetabular osteotomy directly depend on how the acetabulum was reoriented.

There may be an optimum position for the acetabulum that will maximize the benefits and long term success rates of acetabular osteotomies. This position may depend on many factors. The dysplastic geometry of the acetabulum is one important factor. Some acetabula are mainly deficient anteriorly, whereas others provide poor lateral coverage.[15,33] Presumably, increasing coverage where coverage is deficient should decrease pressures, but this hypothesis has not been proven. Another important factor may be the balance between providing effective load-bearing surface, ensuring that the hip joint is stable, and allowing for sufficient range of motion (ROM). The range of loads[3,5,18] supported by the hip joint and the amount of time spent supporting each load also must be considered.[22] Reorienting the acetabulum to optimally support loads during gait may make the joint suboptimal for supporting loads during other activities of daily living. Quantitative methods are needed to help the surgeon reorient the acetabulum and to improve the long term success of acetabular osteotomies.

The geometric characteristics of dysplastic hips are known to be variable and complex. These characteristics can be assessed qualitatively by reconstructing the three-dimensional geometry from computed tomography (CT) data. This qualitative assessment can be valuable in planning treatment, so CT examinations of patients with hip dysplasia are performed commonly. Several methods have been proposed to estimate contact pressures in the hip joint using the CT data.[9,24] One of these methods has been shown in a laboratory study to predict measured contact pressures in the hip joint.[24] This method represents the full three-dimensional geometry of the acetabulum, including the acetabular notch, and can be used to predict the acetabular orientation that minimizes contact pressures (Fig 1).

To determine the factors that may be important when planning acetabular osteotomies based on contact pressures, the following questions were addressed: (1) What are the differences in acetabular pressures between normal and dysplastic hips during common and uncommon activities?; (2) If pressures are elevated for one activity, are they also high for other activities?; (3) Is the normal hip joint optimally oriented to minimize joint contact pressures for a particular activity?; (4) Does the dysplastic acetabulum only need to be rotated in the frontal plane, or should the acetabulum also be rotated in the sagittal plane to reduce pressures?; and (5) If the acetabulum is reoriented to minimize pressures during the midstance phase of gait are pressures also lowered for other activities?

MATERIALS AND METHODS

Computed tomography examinations of the pelvis were obtained for 82 patients (Table 1). Twelve of these patients were being treated for advanced degenerative joint disease. The contralateral, nonpainful, and radiographically normal hips of these 12 patients were analyzed as normal controls. The remaining 70 patients were being treated for hip dysplasia. All patients with hip dysplasia had hip pain. The lateral center edge angle of Wiberg[41] was calculated for all patients from anteroposterior (AP) radiographs or CT scouts views. To identify differences between normal and dysplastic hips, each acetabulum was classified as normal, intermediate, or dysplastic based on the lateral center edge angle (Table 1). Patients with normal hips were identified as having a lateral center edge angle greater than 25°, patients with hip dysplasia had a lateral center edge angle less than 15°, and patients with intermediate hip dysplasia had a lateral center edge angle between 15° and 25°.[31,41] The patients with hip dysplasia ranged in age from 13 to 45 years (mean, 29 years, standard deviation, 11 years).

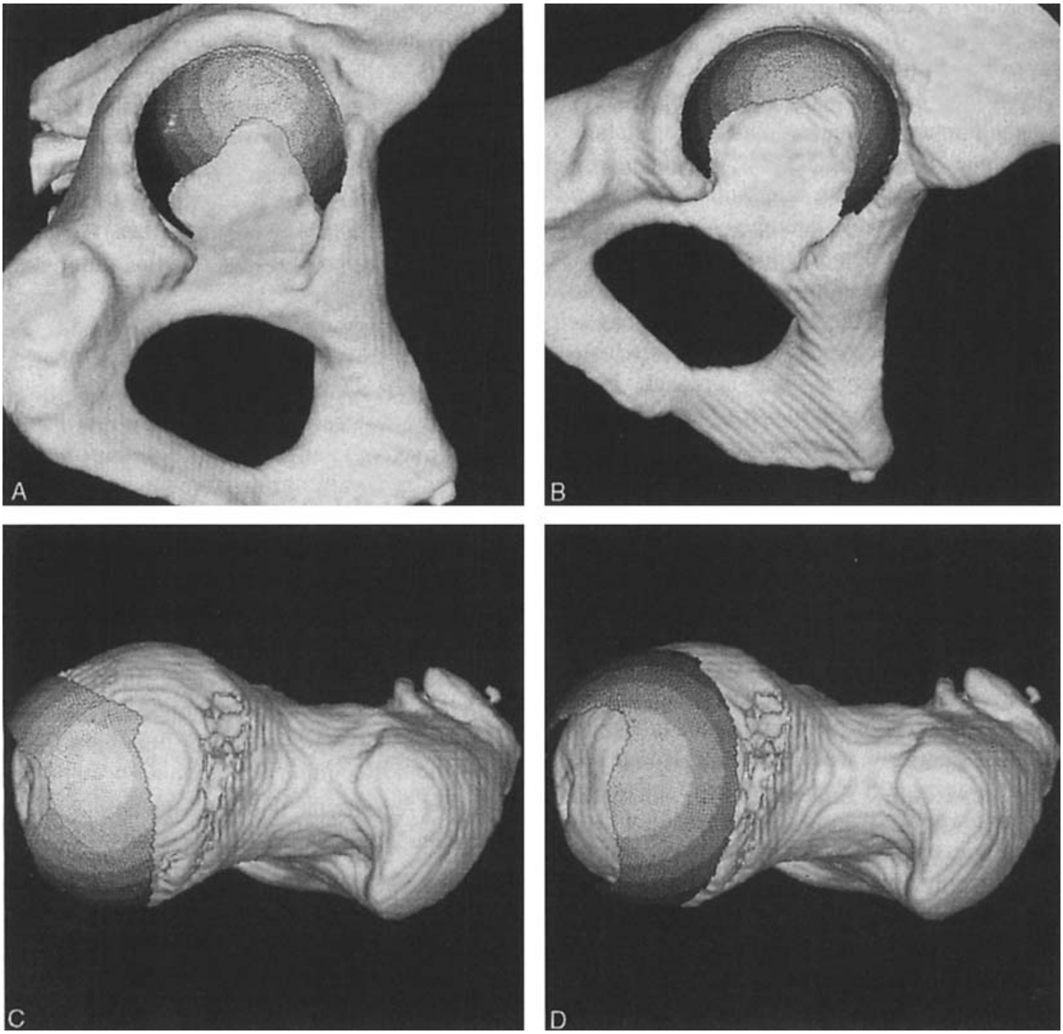

Fig 1A–D. Figures showing estimated contact pressure distributions in a hip joint before and after the acetabulum was reoriented to minimize contact pressures. Before the simulated osteotomy, the lateral center edge angle in this patient was 2°. The simulated osteotomy was 40° flexion and 15° of adduction. Pressures are density coded from light (2.5 MPa) to dark (0 MPa). Pressures were calculated for the midstance phase of gait, and the pressures are shown superimposed over a three-dimensional reconstruction of the patient's acetabulum in the top two images (A, B) and over the femur in the bottom two images (C, D).

The patients with radiographically normal hips ranged in age from 19 to 75 years (mean, 41 years, standard deviation, 20 years).

The CT data were used to generate three-dimensional reconstructions of the acetabulum and femur. The acetabular rim and acetabular notch were digitized using a virtual probe to define the overall geometry of the lunate surface. These points were used to calculate the radius and center of a sphere that best represents the acetabulum. The portion of the sphere that lies within the digitized edges was divided into 0.5 mm^2 patches. This surface was moved 1.5 mm toward the center of the acetabulum to simulate a uniform 1.5 mm thick layer of cartilage.[2] Load vectors

TABLE 1. Comparison of Three Groups

Group	Number (gender)	LCE (°)	Age (years)	Radius (mm)	BW (N)
Dysplastic	51 (44 female, 7 male)	5.6 ± 5.1	28.7 ± 10.8	25.6 ± 3.6	577 ± 118
Middle	14 (13 female, 1 male)	20.9 ± 3.0	37.5 ± 17.4	24.1 ± 1.6	575 ± 95
Normal	13 (7 female, 6 male)	31.8 ± 4.6	40.5 ± 20.0	25.1 ± 2.0	602 ± 104
p value		≪0.001	0.01	0.31	0.75

LCE = lateral center edge angle; BW = body weight.

representing three phases of gait, stair ascent, and three variations of stair ascent loads (adduction of the abducted hip, flexion of the extended hip, and external rotation of the neutral hip) were used to represent a range of common and uncommon activities of daily living.[4] Each of these force vectors represents the resultant force at the hip joint in static equilibrium with the major muscle and gravitational forces.[4] The force vectors were scaled by the individual's body weight, but they were not modified to account for individual variations in muscle insertions or origins or muscle cross sectional areas. The force vectors were distributed over the lunate surface based on the angle between the applied load and the normal load to the surface at each patch. Individual surface patches were included if the calculated pressure at that point was compressive and above a threshold of 0.5 MPa. The contact area and peak pressure were calculated for all 82 patients for each of the seven loads. This method of calculating contact pressures in the hip joint has been shown to predict experimentally measured contact pressures in normal and dysplastic hip joints.[24]

To simulate different osteotomies, pressures were recalculated for several different possible positions of the acetabulum. A simple search algorithm was used to find the acetabular reorientation that minimized contact pressures for each type of load. Rotations were kept within realistic surgical limits of 45° in the frontal and sagittal planes. The optimization was performed three times. The first time, only adduction of the acetabulum (rotation in the frontal plane to increase lateral coverage) was allowed. The second time, only extension (rotation in the sagittal plane) was allowed. The third time, adduction and extension (rotation in the sagittal plane to increase anterior coverage) were allowed.

Unpaired t tests were used to identify differences between normal and dysplastic hips, differences between pressures during different activities, and to compare rotations needed to minimize pressure for the different osteotomies.

RESULTS

Patients with normal hips were older on average, but the radii and body weights were not different from the patients with hip dysplasia (Table 1). The total area of the lunate surface was 26% greater in normal hips compared with dysplastic hips (Fig 2, $p < 0.001$). Pressures were 12% to

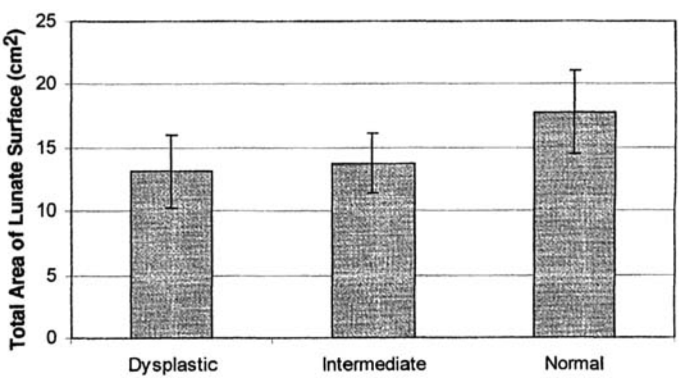

Fig 2. Graph showing that the total loadbearing area of the lunate surface of the acetabulum was 26% smaller in dysplastic hips compared with normal hip joints ($p < 0.001$).

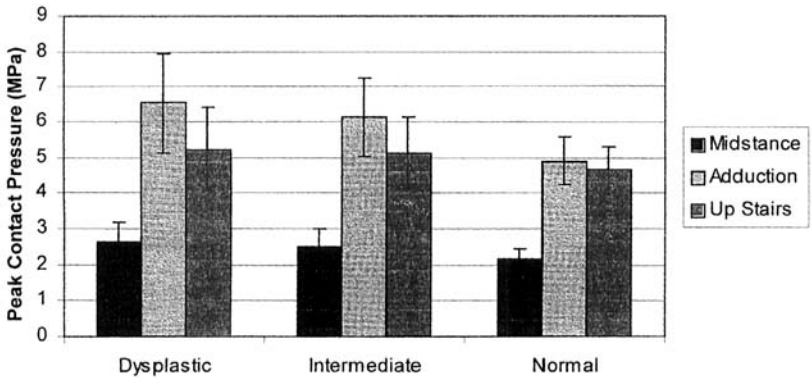

Fig 3. Graph showing that estimated peak contact pressures in the hip joint for loads representing the midstance phase of gait and adduction of the abducted hip were 23% and 33% higher in dysplastic hips compared with normal hips ($p = 0.01$ and 0.003). In contrast, peak pressures during simulated stair ascent were similar in dysplastic hips and normal hips ($p = 0.25$).

33% higher in dysplastic than normal hip joints (Fig 3) for the seven activities that were simulated. These differences were significant for all but the loads representing stair ascent. For the midstance phase of gait, pressures were 23% higher in the dysplastic hips.

Contact pressures for similar loading conditions, such as all phases of gait, were related linearly (Table 2). This suggests that pressures for one of the activities can be predicted from linear regression equations and pressures for similar but different activities. In contrast, moderate errors can be expected if the pressures for the midstance phase of gait are used to predict pressures for dissimilar activities such as stair ascent (Fig 4).

TABLE 2. Slopes, y Intercepts, and Correlation Coefficients for Linear Regressions Between Estimated Peak Contact Pressures During the Midstance Phase of Gait and Other Simulated Activities

Activity	Slope	Y Intercept	R^2
Toe off	1.20	0.01	0.98
Heel strike	1.25	0.06	0.99
Adduction	2.35	0.3	0.73
External rotation	2.17	−0.04	0.99
Flexion	2.60	−0.4	0.93
Upstairs	1.96	0.23	0.86

Allowing for only adduction (rotation in the frontal plane) of the acetabulum, patients with dysplastic hips required an average rotation of 20° to minimize pressures, patients with intermediate hip dysplasia required 13°, and patients with normal hips required −2° (Fig 5). Allowing for only extension (rotation in the sagittal plane) of the acetabulum, patients with dysplastic hips required an average rotation of 26° to minimize midstance pressures, patients with intermediate hip dysplasia required 24°, and patients with normal hips required 19°. Allowing for adduction and extension of the acetabulum, patients with dysplastic hips required an average rotation of 19° adduction and 27° extension to minimize pressures, patients with intermediate hip dysplasia required 14° adduction and 26° extension, and pressures were minimized in normal hips with 2° adduction and 19° extension (Fig 5). Pressures were reduced by almost 50% more by increasing anterior and lateral coverage, although anterior coverage reduced pressures only slightly in some hips (Fig 6). Although the analysis suggests that midstance pressures can be reduced in normal hips by extending them, the amount of pressures reduction was small (Fig 6).

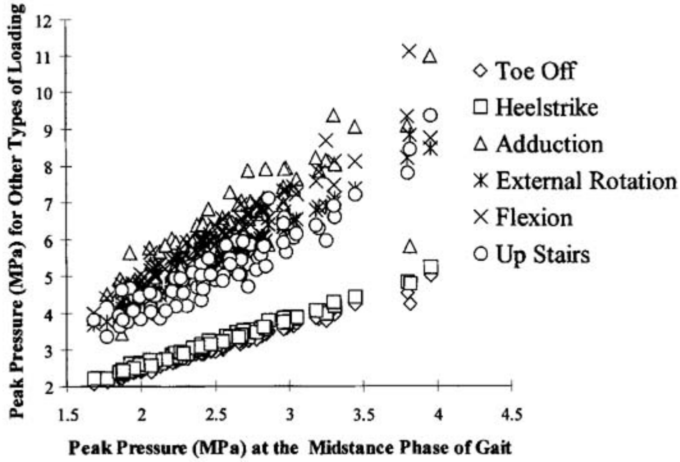

Fig 4. Graph showing strong linear relations between peak hip pressures during the midstance phase of gait and peak hip pressures for other activities that have similar resultant load directions. The correlation was not as strong for activities that have resultant loads that are different from the loads in the midstance phase of gait. The slopes, y intercepts, and correlation coefficients for the regressions are given in Table 2.

When acetabular reorientation was optimized to minimize midstance peak pressures, osteotomies that allow only adduction reduced contact pressures for all the activities considered. Osteotomies that allowed adduction and flexion of the acetabulum provided greater peak pressure reductions for most activities, but increased peak pressures during stair climbing (Fig 7). When the acetabulum was positioned to minimize midstance pressures, the pressures were reduced slightly or became elevated for other activities.

DISCUSSION

The results of the current investigation are consistent with the results of other studies that suggest contact pressures are elevated in dysplastic hips compared with normal hips,[11,22] and also are consistent with the results of studies that show pressures can be reduced by acetabular reorientation.[9,14] Pressures in dysplastic and normal hips were consistent with pressures measured or calculated by other investiga-

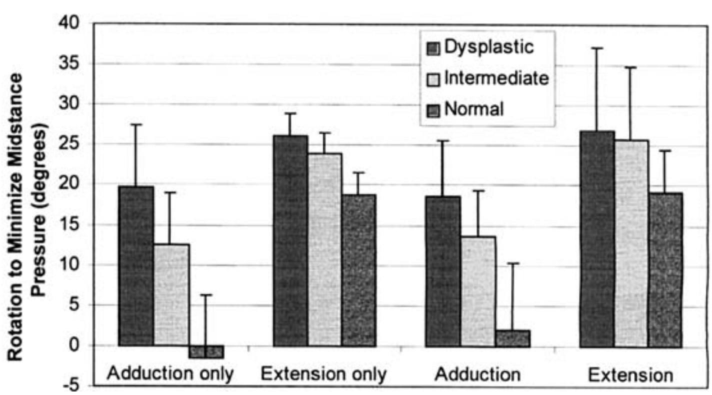

Fig 5. Graph showing the rotations required to minimize contact pressures in normal, intermediate and dysplastic hip joints. When only adduction was simulated, an average rotation of 20° was required to minimize contact pressures in the dysplastic hips. When only extension was simulated, an average rotation of 26° was needed to minimize pressures. When adduction and extension of the acetabulum were allowed, pressures in the dysplastic hips were minimized with an average rotation of 19° in the frontal plane (adduction) and 27° in the sagittal plane (extension). However, even in the normal hips, an average rotation of 19° in the sagittal plane was needed to minimized contact pressures.

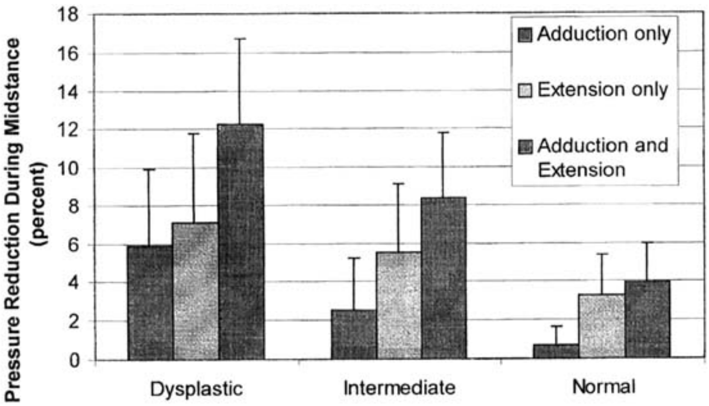

Fig 6. Graph showing that peak contact pressures in dysplastic hips during the midstance phase of gait were reduced, on average, by an additional 50% when the acetabulum was adducted and extended compared with adduction alone or extension alone. In the 13 normal hips, pressures were reduced less than 4% when the acetabulum was reoriented to minimize contact pressures. Although extension only or extension combined with adduction reduced midstance peak contact pressures even in normal hips, the percent reduction was small compared with dysplastic hips.

tors.[13,14,22,34] Estimated pressures spanned the threshold levels of pressure reported by Maxian et al[22] to result in deterioration of the joint.

The estimated contact pressures suggest several important issues to be considered in defining the optimum acetabular reorientation. The reorientation required to minimize contact pressures is variable, with some hips requiring changes in lateral coverage only, and others requiring increases in lateral and anterior coverage. This suggests the need for surgical planning that is specific for each patient. Individualized analysis of contact pressure provides an objective method to plan acetabular redirection. Another important issue is the dependence of contact pressure on load direction. Although osteotomies may reduce hip pressures for a range of activities, there may be some activities where hip pressures actually are increased after osteotomy. This observation supports additional efforts to identify a sys-

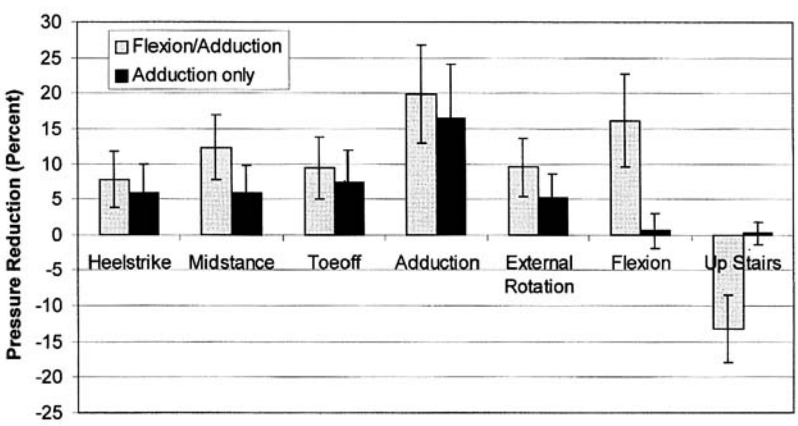

Fig 7. Graph showing the pressure reductions predicted for different osteotomies and different loading conditions. When the acetabular reorientation was optimized to minimize midstance peak pressures, osteotomies that allowed only adduction reduced hip contact pressures for all the activities considered. Osteotomies that allowed adduction and flexion of the acetabulum provided greater peak hip pressure reductions for most activities, but increased peak hip pressures during stair climbing.

tem for weighing the importance of different loading conditions. In addition, the estimated contact pressures after an acetabular osteotomy may suggest postoperative activity modifications that help to avoid loads that result in high contact pressures. Contact pressures in dysplastic hips are related directly to body weight. In some dysplastic hips, especially in overweight individuals, the available surface area is so small that no matter how the acetabulum is reoriented, the pressures cannot be reduced below levels that may result in degenerative changes.[22] This suggests that the combination of small initial area and obesity should be investigated as a risk factor for failed acetabular osteotomy or as a criteria for contraindication to osteotomy.

Based on analysis of normal hip joints, pressures during the midstance phase of gait can be reduced by rotating the socket in the sagittal plane to increase anterior coverage. This supports the hypothesis that the geometry of the human hip has evolved with dual objectives of supporting a range of loads and providing a large ROM. Given that dysplastic hips have a smaller potential loadbearing surface area than normal hips, the optimal acetabular osteotomy may have to sacrifice some ROM or allow for increased pressures during uncommon activities to minimize pressures during the most common activities.

A validated technique for measuring acetabular contact pressures was used, although many other techniques have been described to classify the geometry of dysplastic hips.[12,17,20,25,27,28,31,41] Some of these techniques also have been used to estimate pressures in the hip. Some of these techniques are based on measurements from conventional radiographs, and several of these radiographic measures are associated with a poor prognosis in untreated dysplastic hips.[27,31] Multiplanar radiographs also can be used to better assess the three-dimensional geometry of the acetabulum.[20] Acetabular coverage of the femoral head also can be quantified from CT data[17] and this technique has been used to compare the coverage provided by different types of acetabular osteotomies.[16] Some of these methods can be used, or are used routinely to assess dysplastic hips and plan osteotomies.[27,29] Although measures such as hip congruence are associated with successful osteotomy,[27] it has yet to be shown that specific threshold values for these measurements are sensitive or specific for failure of an acetabular osteotomy. Preliminary evidence suggests that the long term success rates are associated with how the acetabulum was reoriented.[26]

There are several important limitations to the methods used in the current investigation. The acetabula were assumed to be spherical and congruent with the femoral head. This was a good approximation of the hips analyzed in the current investigation, but this is not the case with some severely malformed hips. The methods used to predict contact pressures do not represent the important nonlinear aspects of cartilage or deformation of acetabulum.[10,19] Despite this limitation the magnitudes of stresses were similar to those measured using instrumented prostheses in vivo in humans.[13] Only normal forces were considered in this investigation. Shear forces between femur and acetabulum may play a role in causing joint degeneration. In addition to neglecting shear forces, the methods used in this investigation do not predict subluxation of the hip joint. The need to contain the femur in the acetabulum is a well recognized goal of acetabular osteotomies. Although there may be a relationship between normal contact pressures, shear contact pressures, and subluxation, noninvasive estimates of shear forces and subluxation need to be developed. The forces used to calculate contact pressures were not individualized to specific moment arms and variations in muscle areas that may exist between individuals. Finally, the gait and pelvic orientation of patients with hip dysplasia may be different from patients with normal hips, although data to support this hypothesis were not available. These limitations are being addressed, but are unlikely to change the trends observed in the current investigation.

The optimum position of acetabulum depends on the amount and geometric distribution of the loadbearing surface area, and the type of loads that the hip joint needs to support. Individualized preoperative planning of acetabular osteotomies using three-dimensional CT data can be used to calculate the position of the acetabulum that maximally reduces the contact pressures for specific activities. The required reorientation usually is multiplanar and lateral coverage alone usually is insufficient. An algorithm is needed to calculate the relative importance of different loads on the hip joint. Preoperative planning and intraoperative methods to document acetabular reorientation will allow controlled long term followup studies to better define the factors associated with the long term success of acetabular reorientation procedures.

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