Stress Distribution of a Modified Periacetabular Osteotomy for Treatment of Dysplastic Acetabulum

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Abstract

The Bernese periacetabular osteotomy has become popular in treatment of dysplastic acetabulum. However, the polygonal shape of the osteotomy can create osseous gaps when the fragment is repositioned, especially when a large correction is needed. This study compared the stress distribution of a modified periacetabular osteotomy (spherical osteotomy with smooth and round surface) with those of traditional Bernese osteotomy using finite element analysis. Computed tomography images of a standard composite pelvis were used to create the three-dimensional finite-element intact pelvis model. Based on the intact model, finite-element models simulating the modified and Bernese periacetabular osteotomy were created. The von Mises stress distributions of each model were analyzed and compared for a loading condition simulating single-legged stance. The results indicated that the deformity of the modified periacetabular osteotomy model was less than that of the Bernese-osteotomized model. A large gap and high local stress of 17.2 MPa in peak value were found at the most medial corner of the osteotomized site for the pelvic fragment in Bernese-osteotomized model, which is much higher as compared to 7.6 MPa in peak value for the modified osteotomized model. The stress distribution was more uniform surrounding the osteotomized areas for modified periacetabular osteotomy as a result of a more smooth and round surface surrounding the osteotomized site. Additionally, a high local stress of 336.2 MPa in peak value was also found on the most medial fixation screw for the Bernese-osteotomized model, which was much higher as compared to 224.3 MPa in peak value of the modified osteotomized model. The results from finite element simulation were consistent with clinical outcomes. Our study demonstrated the superiority of modified periacetabular osteotomy in achieving a more physiological stress distribution, making it a better choice for treatment of dysplastic acetabulum.

Keywords: Dysplastic acetabulum, Periacetabular osteotomy, Finite element analysis, Stress distribution

1. Introduction

The goal of periacetabular osteotomy is to achieve optimal coverage of the femoral head and optimal congruency of the hip joint by reorienting the acetabulum. The Bernese osteotomy is a specially designed technique that is capable of correcting the anatomic deformity of the dysplastic acetabulum. However, the polygonal shape of the osteotomy can create osseous gaps when the fragment is repositioned, especially when a large correction is needed. The Bernese periacetabular osteotomy has become popular since it was first described by Ganz et al. [1] in 1988, and several authors have reported encouraging results [2-5]. However, it is a technically demanding procedure. The polygonal shape of the osteotomy can create osseous gaps when the fragment is repositioned, especially when a large correction is needed [6,7]. Also, the classic Smith-Petersen exposure originally used by Ganz et al. carries a high risk of postoperative abductor weakness [8]. Although the use of modified Smith-Peterson exposure, ilioinguinal exposure, and, recently, direct anterior exposure to spare the abductor dissection have been proposed, we believe that these approaches are still difficult and that surgical exposure can be improved with an alternative approach.

To improve exposure, we have modified the techniques described by Ganz et al. [1] with the use of a transtrochanteric approach because it provides a sufficiently wide exposure to the osteotomy sites, a familiar approach used by most orthopaedic surgeons. This modified technique adheres to the basic principles of adequate repositioning of the dysplastic acetabulum while avoiding or minimizing the known complications of the rotational acetabular osteotomy. In our previous surgical experience in using computer-assisted navigation in the modified spherical periacetabular osteotomy,
the modified periacetabular osteotomy is an effective surgical procedure. The results of serial radiographs indicated good clinical outcome because all ostotomies healed and no patient had a neurovascular complication [9]. Although the clinical results were satisfactory, a thorough understanding of the biomechanical performance of this new type of periacetabular osteotomy will be very informative and helpful for clinical practice. Based on the superiority of the clinical outcome, this study was thus designed to evaluate the mechanical performance of the pelvis after the modified periacetabular osteotomy.

2. Materials and methods

2.1 Generation of the 3-D intact pelvis solid model

The hemi-pelves used were commercially available synthetic products (Model: 3005, 3rd generation, Pacific Research Laboratory, Inc., Vashon Island, WA, USA), which were manufactured from a composite glass fiber/epoxy resin material to form cortices with internal cavity filled with polyurethane foam (Fig.1). The hemi-pelvis was scanned using a GE HiSpeed scanner (General Electric, Milwaukee, WI, USA). A series of 180 scans at 1 mm intervals with a resolution closed to 0.24 mm/pixel were taken in the transverse plane direction. The contours of the cortical and cancellous bone were extracted from the set of CT images and converted into mathematical entities on a personal PC using commercial software, Mimics 6.1 (Materialise Software, Leuven, Belgium, UK). These data were then imported into a finite element (FE) package ANSYS, v 8.0 (Swanson Analysis, Inc., Houston, PA., USA) to generate the pelvis solid models. Two models simulating Bernese-polygonal and modified spherical periacetabular osteotomy were created by modification of the intact pelvis solid models. Three fully-threaded cortical screws (diameter 6.0 mm, length 10 mm) were used to fix the acetabular fragment for both types of periacetabular osteotomy. The cortical bone (composite glass fiber/epoxy resin), cancellous bone (polyurethane foam), and fixation screws (stainless steel) were assumed linear, elastic and isotropic, with elastic modulus of 17 GPa, 100 MPa, and 118 GPa, respectively. Poisson’s ratios were taken as 0.3 [10].

2.2 Definition of modified spherical periacetabular osteotomy

The modified spherical periacetabular osteotomy was performed following our previous surgical technique [9]. The osteotomy was begun at the superolateral portion of the ilium, 1.5 cm from the acetabular ridge with osteotomy in spherical shape. The osteotomy was then extended anteriorly and posteriorly around the circumference of the acetabulum. After the osteotomy of the ilium and the ischium was completed, the fragment was connected to the pelvis only at the pubis. The main corrective displacement is by anterior and lateral rotation, but the fragment could also be shifted more medially. Because the fragment was smooth and round, the correction was obtained without creating gaps at the osteotomy site. After correction of the osteotomized acetabular fragment, three long fully-threaded cortical screws (6.0 mm in diameter and 100 mm in length) inserted distally from the acetabular fragment were used to fix the acetabular fragment to the ilium.

2.3 Definition of Bernese polygonal periacetabular osteotomy

Bernese polygonal periacetabular osteotomy was performed with technique described by Ganz et al. [1]. Three identical long fully-threaded screws inserted from the iliac crest were used to fix the acetabular fragment. The iliac screws started approximately 1 cm from the anterosuperior ilium and were placed 1 cm apart. The two types of fixation of the rotated acetabular fragment are shown as Fig. 2. The modified osteotomy with screws inserted from the acetabular fragment (acetabular fixation) is shown on the right hip, and the Bernese osteotomy with screws inserted from the iliac crest (iliac fixation) is shown on the left hip.

2.4 Loading and boundary conditions

The Bernese-polygonal and modified-spherical FE models (Fig. 3) were generated using quadratic tetrahedral elements.

Figure 1. Photograph showing the synthetic hemi-pelvis and osteotomized fragments following (a) Bernese polygonal osteotomy and (b) modified spherical osteotomy. The fragment created from modified spherical osteotomy is smooth and round.

Figure 2. The diagram shows two types of fixation of the rotated acetabular fragment. The modified osteotomy with screws inserted from the acetabular fragment (acetabular fixation) is shown on the right hip, and the Bernese osteotomy with screws inserted from the iliac crest (iliac fixation) is shown on the left hip.
Biomechanical Evaluation of Modified Periacetabular Osteotomy

The threads and the tips for all fixation screws were not modeled in the FE model in order to simplify the model set-up. The bone/screw interfaces for two models were assumed fully bonded without taking into account the micro-motions. As boundary conditions for the FE model, the nodes situated in the sacro-iliac joint areas were kept fixed to simulate sacral support. A loading condition simulating a single-legged stance with a 4.54 BW (3,246 N) joint reaction force was applied based on data by Mann et al. [11]. The direction of the joint reaction force in their study was given in a coordinate system relative to the femur and had to be transformed accordingly into a direction relative to the coordinate system of the present pelvic model. The loading configuration of our FE model is shown in Fig. 4. Finite element analysis of the postoperative hemi-pelvis and fixation screws was conducted, and the stress distribution for two FE models simulating Bernese-polygonal and modified spherical periacetabular osteotomy was compared.

3. Results

The Von Mises stresses of postoperative pelvis with traditional Bernese- and modified periacetabular osteotomy are shown as Fig. 5. As shown in the figure, the deformity of the modified periacetabular osteotomy model is less than that of the Bernese-osteotomized model. For Bernese-osteotomized model, a large gap and high local stress of 17.2 MPa in peak value was found at the most medial corner of the osteotomized site for the pelvic fragment in Bernese-osteotomized model, which was much higher as compared to 7.6 MPa in peak value for the modified osteotomized model. In addition, high local stress on both pelvic and acetabular fragments surrounding the most medial fixation screw was found for the Bernese-osteotomized model. For the modified periacetabular osteotomy model, however, the results indicated that the stress distribution was more uniform surrounding the osteotomized areas due to a more smooth and round surface.

Figures

Figure 3. Photograph showing the 3-D finite element models created from computed tomography (CT) images. (a) Bernese polygonal osteotomy and (b) modified spherical.

Figure 4. The single-legged stance loading condition used for the finite element analysis. The numbers represent the x, y and z components of the applied loadings.

Figure 5. The Von Mises stress of the postoperative pelvis. (a) traditional Bernese- and (b) modified periacetabular osteotomy. For Bernese-osteotomized model, a large gap and a high local stress shown at the most medial osteotomized site of the pelvic fragment. Additionally, high local stress was also found on both pelvic and acetabular fragments surrounding the most medial fixation screw. In contrast, more uniform stress distribution surrounding the osteotomized areas was found due to a more smooth and round surface for the modified osteotomized model.
Figure 6 illustrates the Von Mises stresses of the fixation screws for pelvis with Bernese- and modified periacetabular osteotomy. As compared to the modified model, a high local stress of 336.2 MPa in peak value was found on the most medial fixation screw for the Bernese-osteotomized model, which was much higher as compared to 224.3 MPa in peak value of the modified osteotomized model.

![Figure 6. The Von Mises stress of the fixation screws. (a) traditional Bernese- and (b) modified periacetabular osteotomy. For the Bernese-osteotomized model, a high local stress was found on the most medial fixation screw.](image)

4. Discussion

Periacetabular osteotomy is a well established procedure for the treatment of adult dysplastic hips. With appropriate techniques performed in properly selected patients, periacetabular osteotomy has the potential to correct the dysplastic acetabulum, relieve pain, improve function, and to prevent osteoarthritic changes from progression [2,5]. Several types of periacetabular osteotomy have been developed, and most of them are considered technically demanding [9,12]. Difficulties arise not only from the complex anatomical structures of the pelvis, but also from the limited visualization provided by traditional surgical approaches in which some of the bony cuts have to be done out of the surgeon’s field of view.

In our previous surgical experience, forty-six hips in thirty-eight consecutive adult patients with hip dysplasia were treated with the technique of modified periacetabular osteotomy at our institution and were followed for an average of 4.2 years [9]. Our osteotomy is spherical in shape, which is similar to the design of the rotational acetabular osteotomy. The smooth, rounded surface allows easy movement of the fragment in all directions without impingement, and it provides a large area of contact that results in rapid and predictable bone-healing. In contrast, the polygonal shape of the Bernese osteotomy can result in large gaps, especially when a large corrective displacement is required. The results of serial radiographs indicated all osteotomies healed and no patient had a neurovascular complication. The preoperative and postoperative radiographic measurements showed that, on the average, the femoral head was medialized 6 mm and solid osseous union and good joint congruity as well as good lateral and anterior coverage of the femoral head were achieved. Previous studies [13-15] had demonstrated that the periacetabular osteotomy improved the lateral and anterior coverage of the femoral head and accordingly reduced the normalized peak contact stress in all hips studies. It is therefore reasonable to expect that incorporation of joint congruity assessment in the FE model following periacetabular osteotomy would result in a lower value of peak contact hip stress. Moreover, in the current study, a more uniform and lower stress distribution surrounding the osteotomized area was found for the modified periacetabular osteotomy model, which implies the superiority of the modified periacetabular osteotomy model. Although the clinical results were satisfactory, no previous study had addressed the biomechanical performance regarding this modified periacetabular osteotomy.

As computer technology advances, the prospects for more realistic modeling of bone diseases are encouraging. Patient-specific simulations of surgical procedures are now feasible, particularly using computed tomography and magnetic resonance imaging (MRI) techniques. Given the geometric nature of residual dysplastic hip deformity, the FEA model derived from the reconstruction of 3-D CT images may be helpful for objectively analyzing the stresses in structures with complex shapes, loading and material behavior. Finite element analysis models have been applied extensively in orthopedics and have proven effective for predicting musculoskeletal mechanics in unusual circumstances [16-21]. However, previous literature addressing mechanical performance following periacetabular osteotomy with use of FEA was lacking.

In the present study, commercially available artificial pelvis was used as a substitute for human pelvis. The material properties of human bone vary with age and gender, creating variability among all subjects, and making it very difficult to achieve reliable and comparable analytic results. Recently, numerous investigations using synthetic bone as a substitute for cadaveric specimens have shown the usefulness of these bones for predicting the mechanical characteristics in specified circumstances [22-24]. In the current study, the convergences of the FEMs were justified by the total strain energy of the structures. Four models with different numbers of elements and nodes were created to perform the convergence test, and the results of the total strain energy for the four models were all within 5%. The model with the finest mesh was used, and the convergence of the FEM was demonstrated using the above procedures. The screw threads and tips are not modeled because FE models with screw threads and tips will result in a large increase of element number and computation time. The simplified FE models without taking threads and tips into consideration may have an impact on the analytic results for local area close to the screw/bone interface. However, we believe these may not cause a global effect on the resultant FE analysis.

As shown in Figs. 5 and 6, our results demonstrated that the stress distribution of the modified periacetabular osteotomy model was more uniform at the osteotomized site due to a...
more smooth and round surface. Furthermore, the fixation screw exhibited a much higher local stress for the Bernese-ostearthrotomized model. From the viewpoint of biomechanics, a better clinical outcome of the modified periacetabular osteotomy might be attributed to its superior biomechanical performance. Practically, in addition to the superior mechanical characteristics, there are several advantages for this new modified periacetabular osteotomy: (1) the spherical shape of osteotomy, (2) improving union rate due to a large area of contact, (3) avoiding the injury to the intraarticular structure, (4) avoiding the development of osteonecrosis after the rotational acetabular osteotomy. The smooth, rounded surface allows easy movement of the fragment in all directions without impingement. Although the clinical results were satisfactory, a thorough understanding of the biomechanical properties of this new type of periacetabular osteotomy will be very informative for clinical practice. Based on the superiority of the clinical outcome, this study was thus designed to evaluate the mechanical performance of the pelvis after the modified periacetabular osteotomy.

Several factors that may affect the FEA results of the current study need to be pointed out. First, the geometry and the linear, elastic, homogeneous material properties of a standard composite pelvis were used instead of those of pelvis from an actual patient. The benefit of using a standard composite pelvis was to eliminate the variations in between subjects. On the other hand, the drawback was the overlook of the effects of non-linear, inelastic, and non-homogeneous material properties of the bone. Second, the only loading condition considered was the single-legged stance of the gait. Further investigation on the effects of other loading conditions might be necessary in the future. Third, the bone-screw interfaces were assumed fully bonded without taking into account the loosening of the fixation device. Therefore, the results from the FEA might only be interpreted under the well-fixed condition without screws loosening. Fourth, our FEA models were not validated because it was almost not possible to access the human cadaveric pelvis with dysplastic acetabulum to perform an experiment with related periacetabular osteotomy. As it may have an impact on the reliability of FEA results, a further experimental investigation with cadaveric pelvis identical to our FEA configurations deserves to be performed. Last, the force transferred onto the bone via attached muscle was not considered in the FE model. The attached muscles could balance the distributions of stress and strain in the pelvis during gait motion [26]. Although the simplification of the FE model without taking the attached muscle into consideration might definitely affect the pelvic biomechanical response, the results from this finite element simulation were based on an objective to provide a way to eliminate the problems encountered with periacetabular osteotomy technique as a clinical treatment substitution.

5. Conclusion

The results from finite element simulation were consistent with clinical outcomes. Our study demonstrated the superiority of modified periacetabular osteotomy in achieving a more physiological stress distribution, making it a better choice for treatment of dysplastic acetabulum.

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References


