HIP JOINT CONTACT PRESSURE DISTRIBUTION PRIOR AND AFTER TRIPLE OSTEOTOMY

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ABSTRACT

A 3–D reconstruction method based on CT scans was used to compute the femoral head coverage for dysplasic hips prior and after reconstruction surgery. The triple osteotomy technique was used to “reorient” the acetabulum of severe dysplasic hips. After 3–D reconstruction of the pelvis and the medial part of the femur, a finite element model (FEM) was created which allowed for a static analysis contact study to quantify the contact pressure distribution in the hip joint. After 3D reconstruction of the pelvis and the medial part of the femur, using a specialized software MIMICS (Materialise), a finite element model (FEM) was created with ABAQUS/CAE (Abaqus Inc.). A material assignment was performed for each element. A solution was found to account for the presence of the cartilage layers. The FEM allowed for a static and dynamic analysis contact study to quantify the contact pressure distribution in the hip joint.

Keywords: hip contact pressure, hip dysplasia, triple osteotomy, 3D bone reconstruction.

INTRODUCTION

Instability of the hip and severe dislocation is associated with acetabular deformities (acetabular dysplasia). The femoral head is poorly covered by the acetabulum and concentrates weight-bearing forces over a small area of the articular cartilage \cite{1},\cite{2}. Articular cartilage normally functions within a range of mechanical stress. When the stress threshold of cartilage is exceeded osteoarthritis develops. Correction of the problem may be treated by different methods. A widely used method involves reorientation of the acetabulum by performing a triple osteotomy. Pelvic osteotomy is performed to relieve pain and avoid joint luxation by improving the contact pressure distribution and the femoral head coverage \cite{3}. Armand et al \cite{3} analysed the effect of periacetabular osteotomy on hip dysplasia using a discrete 2–D element model. Their technique modelled a two dimensional representation of the hip contact surfaces as a series of linear elastic springs distributed over the contact area (Winkler elastic foundation model). Hsin et al \cite{4} used also two dimensional analyses based on antero-posterior radiographs. They found the mean values of the absolute stress for normal hips to be around 1.38MPa and the area of the weight bearing surface to be around 15.7cm\textsuperscript{2}. Wang et al \cite{5} developed a two dimensional analytical model for the human hip stress analysis in the sagital plane. They assumed a number of simplifying hypotheses like uniform thick linear elastic cartilage over perfectly rigid femoral head. The peak contact stress calculated for a 70 kg patient with this model was 7.1MPa. Mavcic et al \cite{6} considered the center–edge (CE) angle of Wiberg \cite{9} to be the decisive factor influencing...
the hip contact stress. They used a simple 3−D model to evaluate the peak stress in dysplastic hips and compared the results with the healthy hips. Their model assumed a sinusoidal contact pressure distribution of the form

\[ p(\gamma) = p_0 \cos \gamma \]

Some of these studies made significant progress towards determining the effects of hip reorientation on the contact stress acting on the joint bearing surfaces. But, because of their lack of detail and the numerous simplifying assumptions, they provide only rough estimates of what really happens in the hip joint in terms of contact pressure distribution and contact area. The main goal of this study is to assess and compare the contact pressure in the dysplasic hip joint prior to and after restauorative triple-osteotomy surgery by using 3−D models tailored for each individual case. In this way, the efficiency of the surgical procedure may be precisely evaluated and validated. Also, the addition of mechanical analysis to the preoperative planning has the potential to improve the clinical outcome.

PATIENTS AND METHODS

Three patients with acetabular dysplasia were studied by using three-dimensional computer tomography (CT) reconstructions of the proximal femur and iliac bone after pelvic osteotomies. All three patients were female with ages of 13, 24 and 47 respectively. CT scans were acquired at a thickness of 2 mm from the antero−superior iliac spine to just below the ischial tuberosity. DICOM−formatted files were obtained from the CT scanner and 3D reconstruction and volume integration were carried out using specialized software.

The geometry of each bone was derived from a series of CT scans obtained from the Clinic Hospital for Orthopaedics and Traumatology “Foisor”. The specialized software MIMICS (Materialise) was employed for the visualization, segmentation and 3−D rendering of the CT images. The bone tissue was selected by thresholding. Two limiting grey values (upper and lower threshold) were specified and the pixels having grey values between the two threshold values were treated as bone tissue and collected in a segmentation mask. The next step consisted in manual correction of the mask in order to improve the reconstructed volume and to remove the artefacts appearing mostly around metallic parts (osteointegration nails and wires). From the generated and corrected masks, CAD geometries were created for each bone. A technique employing edge detection was used to generate closed contours for each CT slice. These contours were used to generate the exterior surfaces of the bones which were then meshed with triangular shell elements. The shell meshes were then imported into ABAQUS/CAE (Abaqus Inc.), where 3−D solid meshes were generated from the hollow shell ones by converting the triangular shell elements into tetrahedral solid elements.

Fig. 1. Image showing a “reoriented” hip after triple-osteotomy (left side of the image).

Fig. 2. 3D reconstruction of the entire hip joint after triple osteotomy, showing the material mapping.

The next step was transferring the 3-D solid meshes back to MIMICS, where material assignment was performed for each element. The material assignment or mapping is based on the grey value (Hounsfield units [7, 8]) of each pixel. Two quantitative relationships between the grey value, apparent density and elastic modulus were used in order to assign material properties to each element of the FE model. The first one relates linearly the CT grey values of pixels in Hounsfield units and the apparent density of bone. The second one is a power law
relationship between the apparent density and elastic modulus [10].

\[ \rho = 1.067 \text{HU} + 131 \]

\[ E = 0.004 \cdot \rho^{2.01} \]

Units for \( E \) are MPa and the apparent density \( \rho \) is dimensionless. The Hounsfield scale is a quantitative scale for describing radiodensity. The radiodensity of distilled water at standard pressure and temperature is defined as zero Hounsfield units (HU) and the radiodensity of air at standard pressure and temperature is defined as -1000 HU.

Figure 2 shows the 3D reconstruction of the hip bones rendered with the material mapping and Figure 6 shows the bone density histogram for the femur of one patient. Computer manipulation of the data allowed for preoperative visual assessment of acetabular shape, assessment of potential congruency between femoral head and acetabulum, and evaluation of joint surface coverage, which is directly related to the weight bearing capacity of the joint. With the help of Finite Element Method it was possible to calculate and compare the stresses appearing under the same loading conditions in the dysplasic hip joint before and after surgery.

The entire process from CT images to FEM analysis is synthesised in figure 3.

Because of the relatively high irradiation dose a patient is exposed to during CT scanning, only post-operator CT images were obtained, the preoperator clinical investigation being performed on AP radiographs. In this situation, the result of the 3D modelling revealed only the postoperator bone positioning and alignment. In order to be able to compare the pre and post-operator cases, the preoperative situation was evaluated using the same reconstruction model but using a different alignment of the iliac bone relative to the femur. That is the iliac bone was rotated in the coronal plane with an angle equal with that corrected during surgery.

The 3–D reconstruction of the bones cannot create the cartilage layers existing on the bearing surfaces of femoral head and acetabulum. To account for the presence of cartilage, in the finite element model an exponential pressure–clearance relationship was defined for the contact pair. This relationship simulates a “softened” contact in which the contact pressure is an exponential function of the clearance between the surfaces.

This model is shown in figure 5. The clearance \( c_0 \) at which the contact pressure becomes positive was taken to be 3.5 mm (the approximate cartilage thickness measured on CT images).

RESULTS

The hips of three patients with acetabular dysplasia were evaluated before and after triple-osteotomy surgery. 3–D FEM models for proximal femur and iliac bone were
created from CT images for each studied case. Data such as femoral head coverage and anteversion, mean and maximum contact pressure, cartilage thickness or the CE angle of Wiberg were recorded and compared.

Figure 11 shows a typical contact pressure distribution on the femoral head. The two pressure peaks that can be observed are caused by the geometry of the acetabulum inner surface. In table 1 there are listed the main geometric parameters, for the three patients, depicted both from CT scans and AP radiographs.

The CE angle of Wiberg was first measured on the AP radiograph and then verified on the 3-D joint reconstruction. The difference between the two measurement methods was no more than 5%.

The apparent bearing area was measured using the closed polyline contours obtained from the CT slices. The perimeter $p$ of each polyline was evaluated taking into consideration that only a fraction $f$ of it is situated inside the bearing area. The fraction $f$ of each contour was determined from the CT slices. Gathering all the necessary information, the bearing area was calculated using the next relation:

$$A_b = \sum_{i=1}^{n} p_i \cdot f_i \cdot \delta$$

where $\delta$ is the distance between two consecutive slices.

The peak pressure difference between the measurements was about 30%. The change in the orientation of the acetabulum mainly occurred in the frontal plane. In all cases osteotomy decreased the peak contact pressure and increased the contact area.
Fig. 8. CT slices showing femoral head coverage in coronal (up) and axial (down) planes.

Fig. 9. Radiographs showing the preoperative (up) and postoperative (down) situation.
**DISCUSSION AND CONCLUSIONS**

In order to evaluate the effect of pelvic osteotomy procedures on contact pressure distribution in dysplastic hips, we performed a biomechanical study of patients treated with pelvic osteotomy. We analysed the effect of periacetabular osteotomy on hip dysplasia using FEM simulation of joint contact. Multiple osteotomies and joint realignment require 3D evaluation of the joint bones and cartilage. The modern imaging techniques such as computer tomography or magnetic resonance make it possible to truly visualize skeletal parts in three dimensions. The coverage of the femoral head is difficult to assess quantitatively because of the spherical shape of the two components of the joint and the non-uniformity of the contact stress distribution. The described method allows the measurement of the femoral head coverage and computation of the stress distribution for any given loading scenario.

**REFERENCES**


**Table 1. Main results**

<table>
<thead>
<tr>
<th>Patient</th>
<th>LC</th>
<th>DN</th>
<th>VS</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>13</td>
<td>24</td>
<td>47</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>45</td>
<td>57</td>
<td>68</td>
</tr>
<tr>
<td>Hip resultant force (N)</td>
<td>1575</td>
<td>1995</td>
<td>2310</td>
</tr>
<tr>
<td>CE angle of Wiberg pre-/post-operator</td>
<td>32º</td>
<td>10º</td>
<td>17º</td>
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<tr>
<td>Apparent bearing area pre-/post-operator</td>
<td>865</td>
<td>1024</td>
<td>982</td>
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<tr>
<td>Effective bearing area pre-/post-operator (mm²)</td>
<td>860</td>
<td>1012</td>
<td>976</td>
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<tr>
<td>Mean cartilage thickness (mm)</td>
<td>2.2</td>
<td>2.4</td>
<td>3.5</td>
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<tr>
<td>Peak contact pressure pre-/post-operator</td>
<td>2.86</td>
<td>2.65</td>
<td>5.56</td>
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<tr>
<td>Mean contact pressure pre-/post-operator (N/mm²)</td>
<td>1.95</td>
<td>1.65</td>
<td>1.68</td>
</tr>
</tbody>
</table>

**Fig. 11.** Comparison between contact pressure fields for one of the patients (up: postoperator; down: preoperator – values are in MPa).