A Computer Simulation in Surgery for Human Hip Joint

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Abstract

For patients who have early signs of hip joint disease resulting from structural abnormality, various surgeries for correcting abnormal stress distribution can be useful to prevent the progression of the disease. However, it is difficult to confirm the optimal procedure of surgeries. To deal with this problem, we devised a computer program to support preoperative planning. Hip images obtained by computed tomography were loaded into our program, and a three-dimensional voxel model was created. Then the pressure distribution of hip joint was analyzed with a rigid-body spring analysis (computational non-linear mechanical analysis). This system has a module for performing virtual surgeries. This program allows the hip joint mechanics to be evaluated easily, so that the advantages and disadvantages of various surgical methods could be examined biomechanically prior to surgery. However, this system has several problems that should be solved in the near future.

1 Introduction

For patients who have early signs of hip joint disease resulting from structural abnormality, various surgeries for correcting abnormal stress distribution can be useful to prevent the progression of the disease. To correct this condition, periacetabular osteotomy is frequently performed [1, 2]. This osteotomy involves cutting of the bone around the circumference of the acetabulum and moving the osteotomized acetabular fragment to increase the coverage of the femoral head. It is believed that these procedures have a sound theoretical basis, but it is difficult to confirm the optimal transposition of the osteotomized acetabular fragment. Conventionally, plain X-ray films have been used for preoperative planning. Recently, three-dimensional computed tomography has become available for assessment of the hip joint preoperatively [3]. As mentioned previously, the aim of acetabular osteotomy is to improve mechanical condition of the hip joint. Therefore, it is desirable to include mechanical assessment of the hip joint in the preoperative planning. To deal with this problem, we devised a computer simulator to support preoperative planning.

2 Methods

This computer simulator is composed of two parts (with three programs): Data Preparation part and Mechanical Analysis /Virtual Osteotomy part. All of these programs were written by one of the authors with Visual C++ (Microsoft, Redmond, WA).

Images of the hip joint were obtained with computed tomography. Image data from each slice were stored as a 320 x 320 or 512 x 512 matrix and then were loaded into our program. A threshold was set to distinguish the bones from the other tissues. The program reconstructed automatically the pelvis and the femur as a voxel model (Fig. 1). The joint surface could not be determined automatically by this system, so joint lines were delineated using a mouse and the joint surface was reconstructed as a polygonal model. Figure 2 shows views of the femoral head and the joint surface.

Fig. 1

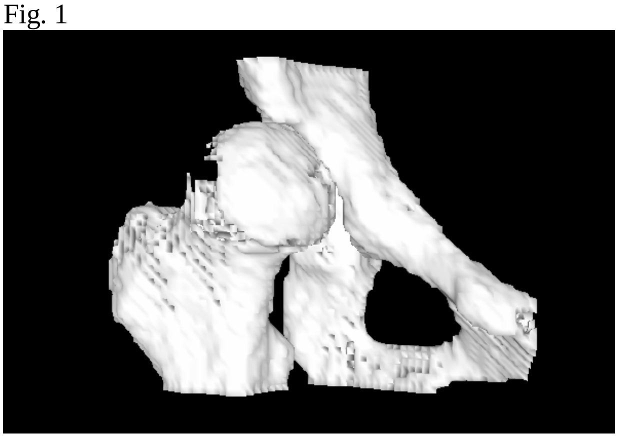
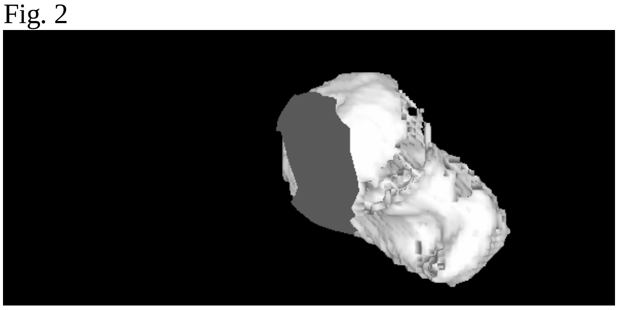


Fig. 2



For mechanical analysis, the joint contact pressure distribution was calculated using the rigid-body spring method of Kawai (computational non-linear mechanical analysis) [4]. The articular surface is assumed to consist of numerous small triangular planes. Each plane has one normal spring and two shear springs. These springs connect components of the joint articulation system that are assumed to be rigid elements.

Formulation of a rigid-body spring model

In addition to the global coordinate system (X, Y, Z), a local coordinate system (x, y, z) was also considered on every contact triangle (Fig. 3). Two rigid elements (G_1, G_2) contact at triangle ABC. An arbitrary point P (X_P, Y_P, Z_P) on triangle ABC moves to P_1 and P_2 after loading (Fig. 4). Because of the rigid body assumption, the displacement vector, $\mathbf{U}_P$, of point P on the contact surface of bodies 1 and 2 moving to P_1 and P_2 can be expressed as a function of the displacement of the selected reference point $\mathbf{U}_G$:

$$\mathbf{U}_P=[\mathbf{Q}]\mathbf{U}_G \qquad (1)$$

where

$$\mathbf{U}_P=[U_{P1},V_{P1},W_{P1};U_{P2},V_{P2},W_{P2}]^t$$

$$\mathbf{U}_G=[U_{G1},V_{G1},W_{G1},\theta_{G1},\varphi_{G1},\chi_{G1};U_{G2},V_{G2},W_{G2},\theta_{G2},\varphi_{G2},\chi_{G2}]^t$$

and the transformation matrix

$$[\mathbf{Q}]=\begin{bmatrix} 1 & 0 & 0 & 0 & (Zp-Z_{G1}) & -(Yp-Y_{G1}) \\ 0 & 1 & 0 & -(Zp-Z_{G1}) & 0 & (Xp-X_{G1}) \\ 0 & 0 & 1 & (Yp-Y_{G1}) & -(Xp-X_{G1}) & 0 \\ 1 & 0 & 0 & 0 & (Zp-Z_{G2}) & -(Yp-Y_{G2}) \\ 0 & 1 & 0 & -(Zp-Z_{G2}) & 0 & (Xp-X_{G2}) \\ 0 & 0 & 1 & (Yp-Y_{G2}) & -(Xp-X_{G2}) & 0 \end{bmatrix}$$

where (X_P, Y_P, Z_P), (X_{G1}, Y_{G1}, Z_{G1}) and (X_{G2}, Y_{G2}, Z_{G2}) are the coordinates of point P, reference point G_1 and reference point G_2, respectively, based on the global coordinate system before deformation.

For each contact area, transformation from the global coordinate, $\mathbf{U}_P$, to the local coordinate, $\mathbf{u}_p$, was achieved through the transformation matrix $\mathbf{R}$:

$$\mathbf{u}_P=[\mathbf{R}]\mathbf{U}_P \qquad (2)$$

where

$$[\mathbf{R}]=\begin{bmatrix} \boldsymbol{l}_1 & \boldsymbol{m}_1 & \boldsymbol{n}_1 & 0 & 0 & 0 \\ \boldsymbol{l}_2 & \boldsymbol{m}_2 & \boldsymbol{n}_2 & 0 & 0 & 0 \\ \boldsymbol{l}_3 & \boldsymbol{m}_3 & \boldsymbol{n}_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & \boldsymbol{l}_1 & \boldsymbol{m}_1 & \boldsymbol{n}_1 \\ 0 & 0 & 0 & \boldsymbol{l}_2 & \boldsymbol{m}_2 & \boldsymbol{n}_2 \\ 0 & 0 & 0 & \boldsymbol{l}_3 & \boldsymbol{m}_3 & \boldsymbol{n}_3 \end{bmatrix}$$

and $\boldsymbol{l}_1$, $\boldsymbol{m}_1$, $\boldsymbol{n}_1$, $\boldsymbol{l}_2$, $\boldsymbol{m}_2$, $\boldsymbol{n}_2$, $\boldsymbol{l}_3$, $\boldsymbol{m}_3$ and $\boldsymbol{n}_3$ are directional cosines between (x,X), (x,Y), (x,Z), (y,X), (y,Y), (y,Z), (z,X), (z,Y) and (z,Z), respectively.

The relative displacement between the matched points P_1 and P_2 was :

$$\boldsymbol{\delta}=[\delta_{sx},\delta_{sy},\delta_n]^t=[\mathbf{M}]\mathbf{u}_P \qquad (3)$$

where

$$[\mathbf{M}]=\begin{bmatrix} -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \end{bmatrix}$$

and δ_{sx},δ_{sy} and δ_n represent the components tangential and normal to the contact surface.

Combining equations (1),(2), and (3), the relative displacement vector $\boldsymbol{\delta}$ is expressed as follows :

$$\boldsymbol{\delta}= [\mathbf{M}][\mathbf{R}][\mathbf{Q}]\mathbf{U}_G=[\mathbf{B}]\mathbf{U}_G$$

Denoting the stiffness constants of normal and shear springs by k_{sx},k_{sy} and k_n ,the stored strain energy, W, is :

$$W=\frac{1}{2}\int_A \boldsymbol{\delta}^t[\mathbf{D}]\boldsymbol{\delta}\, dA=\frac{1}{2}\mathbf{U}_G{}^t\int_A[\mathbf{B}]^t[\mathbf{D}][\mathbf{B}]dA\mathbf{U}_G$$

where

$$[\mathbf{D}]=\begin{bmatrix} k_{sx} & 0 & 0 \\ 0 & k_{sy} & 0 \\ 0 & 0 & k_n \end{bmatrix}$$

and integration is performed on the contact area.

According to the principle of minimum potential energy, the external force, $\mathbf{F}$, which is related to the member stiffness matrix, [$\mathbf{K}$], was calculated as follows :

$$\mathbf{F}=\frac{\partial W}{\partial \mathbf{U}_G}=\int_A[\mathbf{B}]^t[\mathbf{D}][\mathbf{B}]dA\,\mathbf{U}_G=[\mathbf{K}]\mathbf{U}_G$$

Fig. 3

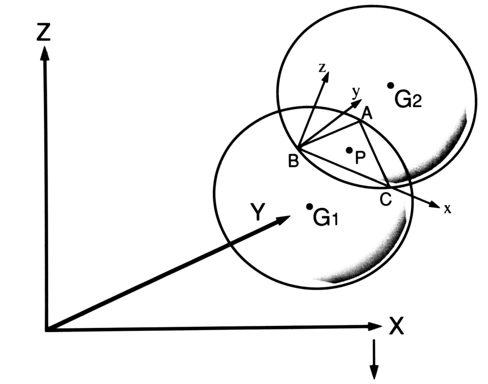
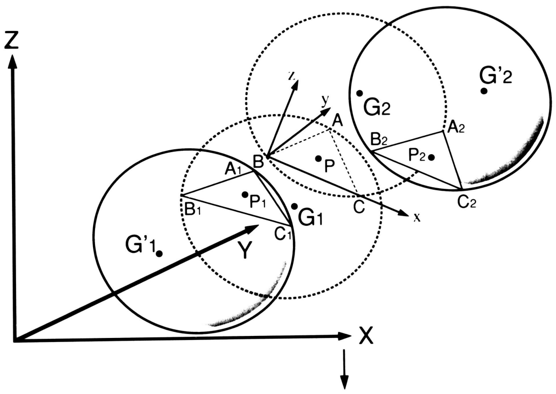


Fig. 4



Algorithm

At the joint contact surface, tensile stress cannot be transmitted. If tensile force is applied to the hip joint, the acetabulum and femur easily become separated. The rigid-body spring model can easily simulate these mechanical characteristics. After the initial stiffness equation was solved to determine the stress distribution, inadmissible solutions for the spring, such as tension on the joint surface, were removed from the model by subtracting their member stiffness matrices from the global stiffness matrix and then repeating the process until no inadmissible stresses were detected.

Modeling of Hip Joint

The reference point for the pelvis was set as the center of the body, and the reference point for the femur was the center of the femoral head. All displacements of the femur were constrained and the load was applied to the acetabulum. The applied load was based on the hip contact force reported by Bergmann [5] during the one-legged stance phase of the normal walking cycle at 3km/h walking velocity. Amount of force was 3.3 times the body weight and the components of loading vector are backward: 0.11, inward: 0.44, downward: 0.89.

Osteotomy simulation

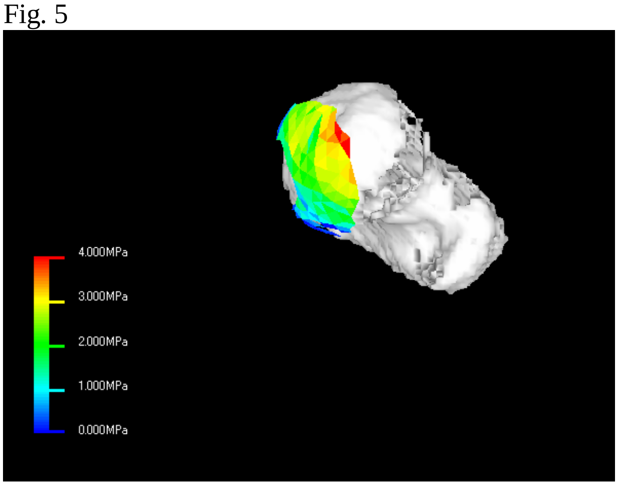
Osteotomy simulation is conducted by cutting the bone and by moving the acetabular fragment on the computer. In this software, the cut surface can be chosen among the flat plane, cylindrical surface and spherical surface. The osteotomized fragment of the bone can be rotated and/or translated as needed.

In the simulation of the rotational osteotomy of acetabulum, the first step is to choose the acetabulum as a target bone, and the second step is to choose the spherical surface as a cut plane. The third step is to set the cut plane at the osteotomy site and cut the acetabulum (Fig. 3), while the final step is to move the osteotomized acetabular fragment and the articular surface. In this study, the diameter of the cut plane was 40mm and the center of the cut plane was set at the center of the inscribed sphere to the acetabulum. To determine the optimal transposition of the acetabular fragment, a peak pressure was calculated for every 5 degrees of rotation of the acetabular fragment.

3. Results

Figure 5 shows an original contact pressure distribution of the example case that was shown in Fig. 1and 2.

Fig. 5



Virtual osteotomy was performed in this patient. The osteotomy is shown in Figure 6. The osteotomy plane for the pelvic bone was spherical with a 40-mm radius. The acetabular fragment was rotated 25 degrees anteriorly and 15 degrees laterally. This increased coverage of the femoral head caused decrease in the peak pressure and the pressure distribution became less unequal (Fig. 7).

The peak pressure was predicted to decrease to 2.28 MPa from a peak pressure before operation of 4.03 MPa.

Fig. 6

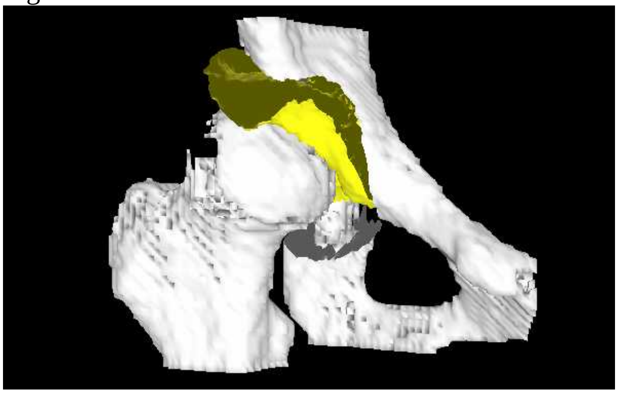


Fig. 7

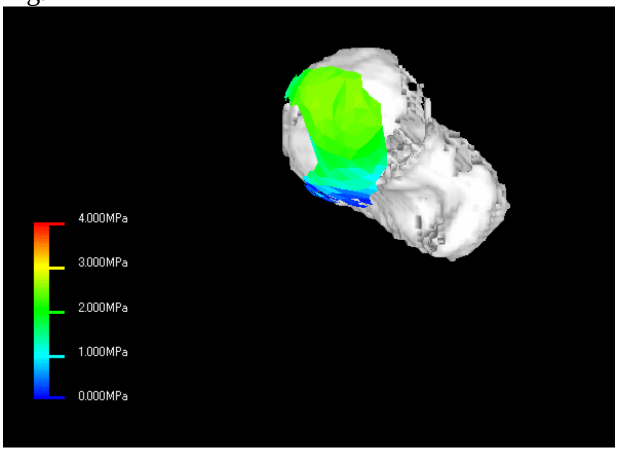
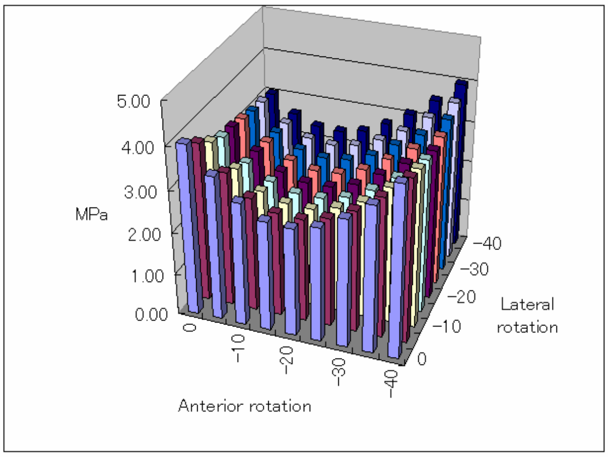


Figure 8 shows the peak pressures that were calculated for every 5 degrees of rotation of the acetabular fragment. The peak pressure was lowest with 25 degrees of anterior and 15 degrees of lateral rotation. However, low peak pressure zone spread from 15 to 25 degrees anterior and from 15 to 20 degrees of lateral rotation.

Fig. 8



4. Discussions

Klaue et al. reported a computer program that could simulate the coverage and the congruency of pelvic osteotomy for preoperative planning [3]. Their program could only show the relationship between the articular surface of the acetabulum and the femoral head three-dimensionally. Our simulator program is more advanced and also incorporates a mechanical analysis module to predict the results of osteotomy [6, 7].

In the actual operation, osteotomy cannot be performed exactly as planned at the present time. However, computer navigation systems and robotics are continuously improving. If this program will be linked to computer navigation system, it will become more useful to determine the most appropriate treatment method for coxarthrosis with acetabular dysplasia.

References

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