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The Comparative Analysis of a Novel Acetabular Component Against Hemispherical Component in Case of Extensive Acetabular Bone Defects – A Study Of Finite Element Analysis

Regular Paper

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Received 2 Aug 2012; Accepted 22 Oct 2012
DOI: 10.5772/54561
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Abstract The purpose of this study was to evaluate the design of a cup using finite element method and to analyze possible effects of joint loading postoperatively, and its initial mechanical stability, so as to direct its further optimization.

Finite-element (FE) models of the cup with three wings and the hemispherical cup were created to calculate the stress patterns during a normal gait cycle. The stress in the acetabular components were analyzed and compared.

The FE analysis demonstrated that all kinds of acetabular components had the same trend for stress and strain. The stress of the wings increased gradually from rim to root. Its peak stress was significantly lower than the yield force of the Co-Cr-Mo alloy at the joint between the wing and the shell. The graft portion near the acetabular component was subjected to higher stress conditions. The contact stresses were found to be decreased with a reduced abduction angle of wings. The cup with wings of abduction angle of 15° had lower stresses compared with other cups.

The cup with wings is a reliable option for the reconstruction of the acetabulum with extensive bone socket defects. The reduced abduction angle of wings helps to decrease the stress of the cup with wings. The FE analysis is a useful tool with which to address these issues.

Keywords Acetabulum, Component, Revision, Finite Element Analysis

1. Introduction

For the arthroplasty surgeon, acetabular revision is the most difficult aspect of the hip reconstructive surgery,
especially in the presence of severely deficient acetabular bone stock that could compromise a future acetabular reconstruction [1]. Patients with severe acetabular deficiency and poor bone quality require more complex alternatives for revision. A variety of approaches have been introduced to restore the hip biomechanics closer to normal. These approaches mainly include structural bone grafts [2, 3], metal acetabular reinforcement rings and cages [4], placement of the acetabular component in a high hip center [5], jumbo cups [6], bilobed cups [7], use of trabecular metal acetabular augments [8], and the triflange cup. Results of these techniques described in literature vary.

Structural bone grafting has the potential to restore bone stock for future revisions, but the greater the extent of coverage of the acetabular component by the graft, the greater the rate of late failure. In an earlier report, high placement of an acetabular component in a patient with severe acetabular bone loss contributed to avoiding bulk structural bone grafting and obtaining maximum contact with the native acetabular bone [9]. However, this procedure had a few shortcomings, such as limb-length discrepancy and the instability of the hip caused by femoral impingement on the pelvis. Revision with special acetabular components, especially uncemented acetabular components has been considered as the main management for severe deficiency of acetabular bone stock.

Although the majority of acetabular revisions are performed using an uncemented hemispherical acetabular implant with ancillary fixation, their disadvantages that include high cost, technical difficulties due to incomplete contact, component malposition and excess bone removal to achieve an ideal fit, limit the use of this technique in modern revision surgery. Therefore, we designed a novel acetabular component consisting of a porous metal shell with three wings and an all-polyethylene liner that had been introduced for acetabular revision in a case of massive bone loss and which attained a satisfying mid-term clinical result in our previous study [10]. But the long-term results and its mechanical features are still unavailable.

The effect of the load on the cup after acetabular revision surgery is important to achieve a better clinical result, especially to the initial stability of the cup and integration of the graft. Considering the complex anatomical structure of the pelvis, it is difficult to study its mechanical features in vivo. Finite element (FE) modeling enables the evaluation of stress distribution throughout the total hip replacement (THR) prostheses [11] and an assessment of the geometries and material properties which would be difficult or time-consuming to test experimentally. Hence, FE analysis was conducted as the basis of this study to evaluate the design of the novel acetabular component based on comparison with traditional hemispherical acetabular cup, and to describe the general rules of stress applicable to these cups and the individualized features of the novel cup. In addition, the abduction angle of wing has important effect on the stress transfer of the cup. So, we tried to change the angle from 30° used in current cup to 15° and 45° in order to determine the change of the stress in the cup. Therefore, by this study, we hope that the results might help to direct further optimization of the design for the type of cup.

2. Materials and Methods

Generating the finite element models of the acetabular components

To evaluate stress behavior of the acetabular components, we created FE models of the hip with acetabular bone stock loss. The standard FE mesh was based on digitized sections of a normal male pelvis. This research focused on the analyses of acetabular revision components, and for this reason we intercepted the left acetabulum area from the pelvis model and reduced it into a regular hexahedron. The nodes on the superior acetabular rim were moved 25mm into the material to simulate the acetabular superolateral severe bone loss with a maximal diameter of 25mm.

As the main research objects, the FE models of the acetabular component with three wings and hemispherical acetabular component used more nodes and element mesh density in order to calculate stress more accurately. These components were respectively represented by 20,000 and 19,000 SOLID92 units which are high-level tetrahedral elements, with nodes freedom of UX, UY and UZ that mean the displacement in Cartesian coordinate system. This kind of tetrahedral element has various mechanical abilities including plasticity, creep, stress hardening, large deformation and large strain. The materials of acetabular components are Co-Cr-Mo alloy, which are widely used for medical prosthetic implant devices. The outer diameter of hemispherical acetabular component is 54mm. The hemispherical part of the cup with wings has outer diameters of 54mm. The abduction angle of the wings for the novel cups used in the study are 30° and 15° respectively, with maximum wing length of 25mm, so these acetabular cups are able to be used for reconstructing acetabulum with maximal bone deficiency diameter of 79mm. All kinds of components used in the study were sponsored by the manufacturer (Beijing Lidakang Technology Co., Ltd) and had all-polyethylene liners with inner diameters of 28mm and a thickness of 9mm.

For simulating clinical operation, these acetabular prostheses were inserted into acetabulum models with eversion of 45° and anteflexion of 30°. Meanwhile, to provide further understanding of the effect of the cup on the bone graft, the remaining gaps were filled with freeze-dried allograft.
Boundary conditions and applied force

The models were assumed to have fixed support at the sacroiliac joint and the pubic symphysis. The relative sliding between the prostheses and bone and between the wings and graft were not taken into account, thus these interfaces of acetabular prostheses were considered to be fully bonded. The models did not include muscle forces.

The hip force acted on acetabular cup through the cobalt-chromium head. The direction and magnitude of the hip force during a normal walking cycle were based on the data reported in literature [12]. Our previous research had shown that stress behaviors of the cup with wings were similar during a variety of phases of a normal walking cycle [13]. The values of stress during 2, 3, 4, and 5 phases were obviously higher than that during 1, 6, 7, and 8 phases, but there were no significant differences within the same group. So, in this study, two hip forces were chosen from the two groups to represent a high load and a low one, respectively, in order to avoid repetitive work. We assumed the weight load of the male with a normal average height is 65kg; in this case, the hip forces that we chose from phases 1 and 2 of a normal walking cycle were 2158N and 426N, respectively. The forces were applied through the center of the ball to the surface of the liner corresponding to their directions during a normal walking cycle.

Material parameters

The materials used in the analyses were assumed to be isotropic and homogeneous. All the material properties including the elastic modulus and the Poisson’s ratio were recorded and are detailed in Table1 which is based on current values reported in literature [14]. All material models were assumed to be linear elastic. The stress analysis was performed using the ANSYS software (v10.0; ANSYS, Inc.).

Statistical analysis for data

SAS v 9.1 (SAS Institute Inc., Cary, NC, USA) was used for statistical analysis. The t-test was done to analyze data between two groups and the analysis of variance to data among three groups. The level of statistical significant difference is 0.05.

3. Results

Hemispherical acetabular cup model

In order to ascertain a comparative analysis of the cups, we established a three-dimensional FE model of the traditional hemispherical acetabular cup (Fig.1a). It was observed that, in the cup, the von Mises stress was greatest around the point to which the hip force was directed and decreased gradually from the action center to the cup rim (Fig.1a, b).

![Figure 1.](image)

In addition, a high stress area at the anterosuperior acetabular rim was also noted. The stress was higher when the hip force increased from 426N and 2158N. The von Mises stress consisting of all the individual stress components is non-directional and is a measure of the stress intensity [15]. In the case of hemispherical interfaces, the stress components are defined as normal, circumferential, tangential stress as well as torsional, tilting, and parallel shear stress. The normal stress and the torsional and tilting shear stress are the actual interface stresses. In our model, at the outer shell-bone interface, and the inner shell-liner interface, the normal stresses were greatest in the area to which the hip forces were applied and had a declining gradient from this point to the cup rim. The values of stresses between the two interfaces had no significant difference. The loads transferred through the cup from liner to bone without remarkable decline (Table2).
The acetabular components with three wings

Two FE models of the cups with three wings of which the abduction angle are 30° and 15°, respectively, were generated to calculate the von Mises stress and various shear stresses (Fig.1b, c). All the calculated stress contours of the cup with wings are shown in Fig.2c-f. The results demonstrated the distribution patterns of stress in the hemispherical parts of both the cups, that is, the hemispherical acetabular cup and the one with three wings were almost similar. The magnitudes of stress in the various parts of the novel cup also greatly increased with the change of load from 426N and 2158N (Table2). However, the individual stress components behaved similarly.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** These figures show the stress contours of the three revision cups in two loads. Red represents high level of stress, and blue represents low level of stress. In the hemispherical cup, the von Mises stress was the greatest around the point to which the hip force was directed and decreased gradually from the action center to the cup rim (a, b). The distribution patterns of stress in the hemispherical parts of the two cups with wings were almost similar to that of hemispherical cup. But there were stress concentration regions at the roots of the three wings (c, d, e, f).
Table 1. The mechanical properties for all materials

| Materials          | Young's Modulus (Mpa) | Pascho's Ratio |
|--------------------|------------------------|---------------|
| Co-Cr-Mo alloy     | 200000                 | 0.3           |
| UHMWPE             | 700                    | 0.3           |
| pelvis             | 17000                  | 0.3           |
| dry-freezed allograft | 230                  | 0.25          |

Table 2. The von Mises stress and main shear stresses of three types of cups in both loads

| Stress(Pa) | hemispherical cup (I) | the cup with wings of abduction angle of 30° (II) | the cup with wings of abduction angle of 15° (III) | P values** (I, II, III) |
|------------|------------------------|-----------------------------------------------|--------------------------------------------------|------------------------|
| Hip force  |                        |                                               |                                                  |                        |
| 426N       | 2158N                  | P values*                                    | P values*                                        | P values*              |
| The von Mises stress |                            |                                               |                                                  |                        |
| at inner interface (A) | 641486                  | 1024246                                      | 22040                                           | < 0.0001              |
| at outer interface (B) | 739542                  | 252329                                       | 78038                                          | < 0.0001              |
| P values* (A, B) |                                  |                                               |                                                  |                        |

Values of various stresses are expressed as mean±SD. The P values* represent the results of t-test performed between the load of 426N and the load of 2158N; the P values** represent the results of t-test performed between the inner interface and the outer interface; and the P values*** represent the results of analysis of variance to data among three cups (I, II, III).

Table 3. The von Mises stress and main shear stress of the wing and graft in two cups with wings

| Stress(Pa) | the cup with wings of abduction angle of 30° (II) | the cup with wings of abduction angle of 15° (III) | P values ** (II, III) |
|------------|-----------------------------------------------|--------------------------------------------------|------------------------|
| Hip force  |                                               |                                                  |                        |
| 426N       | 2158N                                        | P values*                                        | P values*              |
| The von Mises stress |                            |                                               |                                                  |                        |
| of the wing | 1045618                                     | 345238                                         | < 0.0001              |
| Torsional shear stress | 378206                                     | 72419                                          | < 0.0001              |
| of the wing | 886.1                                       | 246.9                                          | < 0.0001              |
| Total von Mises stress | 4817                                       | 726                                            | < 0.0001              |
| of the graft | ±27.1                                       | ±28.6                                         | < 0.0001              |

Values of various stresses are expressed as mean±SD. The P values* represent the results of t-test performed between the load of 426N and the load of 2158N; and the P values** represent the results of t-test performed between two cups with wings (II, III).

Several individualized characteristics were observed in the cup with three wings: (1) The stress concentration regions were found at the roots of the three wings, (2) The stress of the wings increased gradually from rim to root. Its peak stress, but significantly lower than yield force of the Co-Cr-Mo alloy (±450 Mpa), was at the joint between the wing and the shell. (3) As one of the main stresses for the wing, the torsional shear stress was greater at the rim of the wing. The trends of the stress were not affected by the loads acted on cups. (4) The remaining gaps were packed with freeze-dried allograft to simulate clinical acetabular revision surgery, which had the similar distribution laws of the von Mises stress in the novel cups with different abduction angles. The values of stress increased gradually from anterolateral edge to the root where the graft made contact with the cup and was subjected to the peak stress, but it was significantly lower than the stress of the cups (Fig.3). On the other hand, the level of stress for graft was greater in the load of 2158N than in the load of 426N. In Table3 and Fig.6, the various stresses of the graft and wings in two cups with wings are shown.

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The comparative analysis of three acetabular components

To better understand the stress feature of the novel cup, we performed the comparative analysis of the hemispherical acetabular cup, the cup with wings of abduction angle of 30° and the cup with wings of abduction angle of 15°. The various stresses of the three acetabular components have been shown earlier in Table 2. The results of analyses showed that the von Mises stress and three main interface stresses measured in 2158N or 426N loads were in descending orders from the cup with wings of abduction angle of 30° to the hemispherical acetabular cup, to the cup with wings of abduction angle of 15° (Figs. 4, 5). However, the values were lowest in the cup with wings of abduction angle of 15°, although with no significant difference between the cup with wings of abduction angle of 30° and the hemispherical acetabular cup ($P > 0.05$). The stress pattern of cup with wings of abduction angle of 15°, otherwise, was more regular in comparison to that of the cup with wings of abduction angle of 30°. We made an independent analysis for wings and graft in this study, and the results suggested that the values of the von Mises stress or the main torsional shear stress greatly increased in the cup with wings with an abduction angle of 30° compared to the cup with wings of abduction angle of 15° ($P < 0.05$).

Figure 3. These figures show the stress contours of the graft in the two cups with wings in two loads. The stress patterns for the grafts used in the two cups with wings presented almost consistently. The values of stresses increased gradually from anterolateral edge to root where graft contacted with cup and was subjected to the peak stress (a, b, c, d).

Figure 4. The graph shows the variation of the von Mises stress and main shear stresses for the three revision cups in the load of 426N, as calculated with the finite element model. The values of various stresses in the cup with wings of abduction angle of 15° were the lowest.
Figure 5. The graph shows the variation of the von Mises stress and main shear stresses for the three revision cups in the load of 2158N, as calculated with the finite element model. The values of various stresses were the lowest in the cup with wings of abduction angle of 15°.

Figure 6. The graph shows the variation of the von Mises stress and main shear stress of the wing and the graft in the two cups with wings in the load of 426N. The values of various stresses were less in the cup with wings of abduction angle of 15° than the cup with wings of abduction angle of 30°.

4. Discussion

Loosening of acetabular components often leads to bony defects. Management of massive acetabular bone loss in hip revision arthroplasty is a tremendous challenge for the arthroplasty surgeon. To overcome this, surgeons need to reconstruct the support of acetabulum and restore the original hip center of rotation as much as possible. Until now, quantitative assessment of stress behavior of acetabular components has been difficult due to the complexity of the pelvic bone geometry and the associated loading conditions. Technology of FE analysis, as one of the main methods of mechanics, had been successfully applied in many fields, especially in analyzing on irregular bodies. Several models applied in previous analysis were 2-D approaches; as a result, limited information was provided [16]. As software and hardware capacities improve, the 3-D FE calculations have been developed, which are necessary for more applicable results [17, 18].

In this study, we generated 3-D axisymmetric FE models of various cups to simulate the reconstruction of acetabulum with massive superior bone socket loss and calculated its stress pattern. In the clinical setting, however, the bone support and muscle force will affect the stresses to which the acetabular cups are subjected [19]. As numerous studies have pointed out, the FE model of acetabulum reconstructed by morseized bone graft is a simplification of the reality. It does not consider the biological changes which occur within the graft and at its interface [20-22]. In general, slight differences between the previous studies and the present study are probably due to differences in the acetabular cup geometries, material properties and the loading protocols used in the experimental tests and analytical or numerical analyses [23].

We found the stress distribution of the hemispherical cup was consistent with the direction of hip forces and the trend for the von Mises stress and main interfaces stresses increased as the load increased from 426N to 2185N. In the cup, high stress occurred in the area of the anterosuperior acetabular rim. In addition, the result showed the stress patterns of the von Mises stress and various shear stresses at inner and outer interfaces of the novel cup were consistent with the hemispherical cup. Stress concentration of the novel cup existed at the root where the hemispherical part of cup connects with the wings. But the peak value in the area was significantly lower than the yield force of the Co-Cr-Mo alloy, so it has no obvious effect on the stability of cup. The value of stress was not significantly different between inner and outer interfaces. As for the cup with wings, there was a decreasing effect on the stress of the cup with the reduced abduction angle of the wing. In the study, we tried to change the abduction angle of wings from 30° to 15° and 45° respectively. When the abduction angle of wings was 45°, the contours of stress became distorted, obviously due to the high level of stress suffered in the cup. Thus, we abandoned this angle. The results demonstrated that the stress distribution of the cup with wings of abduction angle of 15° was more regular, based on contours of stress.

Stresses are generated in implant materials and bone, and at their interfaces. These stresses may affect the structural properties of the implant/bone system, or bring it to failure at some time in the postoperative period [18]. The novel acetabular component designed by our team for the revision of acetabulum with severe bone defects consisted of a porous metal shell with three wings and an all-polyethylene liner. The hemispherical part of the cup had an outside diameter of 54 mm, the lengths of its wings
were 10-25mm, and so the maximum diameter of deficient acetabulum socket that was reconstructed with this cup reached 79mm. The sharp edge of the wing allowed the cup to insert into the host-bone of the acetabulum, and the remaining gap was packed with impacted morcelized bone grafting. According to Wolff’s law, proper external loadings promote osteoblast activity [24]. Therefore, the amount of bone stock increases accordingly. The wings separated the periacetabular material into quadrants, which was associated with decreased peripheral stresses. Additionally, the load is smoothly transferred along the wing from acetabular cup to appropriate proximal regions of the pelvis, reducing the effect on the graft such that proper stress contributes to improved integration of the graft and initial stability of cup.

Finally, based on results of this study and its clinical application, we concluded that the cup with wings could be used for reconstructing the severe acetabular defects with no need to sacrifice the remaining host-bone of the acetabular socket compared to using extra-large uncemented hemispherical acetabular components. We also found that the cup with wings provided better support to the graft. The combination of this type of cup with morcelized bone graft seems to be a reliable solution for restoring bone stock, relocating the hip center, and stabilizing the cup in revision surgeries with severe acetabular bone deficiency. This study also illustrates that 3D FE analysis is suitable for procuring additional biomechanical information to augment clinical studies, for evaluating implants and for establishing stability prognoses, especially for newly developed prototypes. It provides a theoretical basis for further optimization of the cup with wings. However, we emphasize that the results reported here are preliminary and restricted by an inadequate knowledge of the numerical values of certain physical and biological parameters and by the primitive assumptions of the three-dimensionality of cortical and spong bone. Many factors such as dynamic mechanics analysis and fatigue tests that are closer to the physiological state should be taken into account in future studies. Biomechanical tests using a cadaver specimen may also be needed to validate the FE analysis results.

5. Acknowledgments

Supported by a grant from the Hebei Department of Science and Technology to the Third Hospital of Hebei Medical University (12966116D). We also thank Liu Yueju, Wu Shuaishuai, Xu Bin, and Liu Song for their efforts in data preparation.

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