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Comparison of fragment removal versus internal fixation for treatment of Pipkin I femoral head fractures: a finite element analysis

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Comparison of fragment removal versus internal fixation for treatment of Pipkin I femoral head fractures: a finite element analysis

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Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

Running title: treatment of Pipkin I fractures

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Abstract

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Conclusion: Compared to internal fixation, fragment removal led to greater stress that was more concentrated in the femoral head. This finding may help surgeons in choosing an appropriate treatment from a biomechanical perspective.

Level of evidence (with study design): Basic Science Study III

Key words: Femoral head fracture, Finite element, Three-dimensional, Pipkin

Introduction

Femoral head fracture is a severe, rare hip injury. These fractures occur in approximately 10% of traumatic posterior dislocations of the hip joint.[1,2] The classification originally proposed by Pipkin in 1957 is the most commonly used classification system. It categorizes femoral head fractures into 4 types increasing in severity.[3] Pipkin type I fractures occur inferior to the fovea in the non–weight-bearing portion of the femoral head. Because this is a rare injury, patient treatment and outcome data are limited. The aims of treatment are to reposition the fracture and to restore articular congruency. Often, these aims are accomplished nonsurgically by limiting weight-bearing activities and by physical therapy. Outcomes are good if the fracture is displaced less than 2 mm after reduction and no intra-articular fragments remain. In fractures that require surgery, whether to perform femoral head fragment excision or internal fixation is controversial.[4]

Epstein *et al.* suggested that all traumatic dislocations of the hip require surgery to remove fragments.[1] In contrast, studies conducted by Hougaard *et al.* indicated that internal fixation of fragments led to better outcomes compared to fragment excision.[2] More recent studies showed that internal fragment fixation could achieve positive results and early mobility. Studies comparing conservative treatments, fragment resection, and internal fixation with limited cases have shown controversial results.[5-7] Hence, there is no universally accepted treatment strategy.

Finite element (FE) methods can perform complex biomechanical analyses better than traditional methods.[8-10] This technique has gained in popularity because mechanical properties of the body can be modeled under different experimental conditions. In this paper, we built a three-dimensional (3D) FE model of Pipkin type I femoral head fracture. Our aim was to compare stresses on the femoral head after fragment excision and internal fixation. Results of these analyses may provide biomechanical information that surgeons can use to make treatment decisions. To our knowledge, this is the first biomechanical report to compare the two treatments for Pipkin type I fractures.

Materials and methods

Reconstruction of the FE models

Numerical data of 3D FE models of the hip were based on the CT images of a 28-year-old healthy male volunteer. He was scanned by a Siemens Dual-Source CT scanner (Siemens Medical Solutions, Germany). A slice thickness of 0.5 mm was used with an image matrix of 512 × 512 pixels. Images were obtained from the acetabulum to the upper part of the femur. Sequential cross-sectional images of the human femoral neck were extracted from the CT data by MIMICS software. 3D images of the femoral head were reconstructed after meshing was performed by ABAQUS (Figure 1).

Reconstruction of a 3D numerical model of a Pipkin type I femoral head fracture

A 3D sphere model with a diameter of 10 cm was reconstructed after meshing by using MIMICS software. A 3D sphere was used to cut the 3D femoral head to mimic a Pipkin type I femoral head fracture. Fracture anatomy was strictly consistent with the definition provided by Pipkin in 1957. We performed Boolean calculations at the overlapping parts of the two 3D models. The intersection set was fragmented as illustrated in Figure 2.

Reconstruction of a 3D numerical screw model

A 3D numerical screw model was reconstructed using Solidworks Software and data from the absorbable self-tapping BIOFIX screw (Figure 2). The modeled 3D numerical screw was identical in size to the actual screw. The external diameter was 3.5 mm and the length was 45 mm. The 3D numerical screw model was transferred in stereolithography format to MIMICS and was remeshed.

Reconstruction of implantation

Implanted points of the screws were determined based on the Campbell principle. The implantation points on the fragment were acquired after Boolean calculations between the fragment and the screw. Another calculation was done between the remaining femoral head and the screw to determine the implantation point on the femoral head, which was based on the size of the screw. The screw was implanted manually (Figure 3).

All models and material properties were transferred to ABAQUS in input format. Every planar mesh was transformed to a 3D mesh by using MESH software, and every model was a tetrahedral element. A total of 880,377 elements for the femur, 895,022 elements for the remaining femur, 17,007 elements for the fragment, and 10,471 elements for the screw were used.

Material properties and interfaces

Material properties of the bone were provided by MIMICS. Bone density was calculated based on the CT Hounsfield (HU) values and the equation: ρ (kg/mm^3) = 1.067*HU+131. The relationship between elastic constants and density was described by E (MPa) = $0.09882\rho^{1.56}$. Poisson's ratio was assumed to be 0.3. Material properties of the screw were based on the screw instructions from BIOFIX. The elastic modulus was 8 to 15 GPa. We used the mean elastic modulus (12 GPa) and assumed that Poisson's ratio was 0.3.

In the ABUQS system, the contact force was not set automatically because there was an interface between two elements in space. We redefined the interface using Interaction software. The bone-to-bone friction coefficient was set at 0.3 and the bone-to-screw friction coefficient was infinity, which assumed successful surgical placement.

The load on the femoral head in one gait cycle was calculated as 4 times the body weight. The joint reaction forces of a male adult weighing 700 N in one gait cycle were 0.616 (X), -2.8 (Y), and 0.717 (Z), which totaled 2.872 kN. Because the femoral head was observed in the study, freedom of motion for the distal part of the femur was set to zero. Stress changes on the femoral head after two treatments were analyzed by ABAQUS. Stress distribution maps were created by the software automatically.

Statistical analysis

All data were analyzed with the SAS statistical software version 9.0. The significance level of *P* was set to 0.05. Data were expressed as the mean ± standard deviation. Between-group differences were analyzed by *t*-test. Random points were compared by the Kruskal-Wallis test. This study was approved by the Institutional Review Board of the First Hospital of Jilin University.

Results

Stress distribution maps were created to model the stresses experienced by the femoral head after fragment excision (Figure 4) or internal fixation (Figure 5). Colors indicative of high stress (i.e., grey, red, and orange) were more evident on the femoral head in the fragment excision group compared to the internal fixation group, suggesting that stress on the femoral head was higher in the fragment excision group. Colors indicative of high stress in the fragment excision group were most prominent along the fracture line.

To test stresses along the fracture line, 13 fixed points were selected every 15 degrees in a semicircular pattern from 3 to 9 o'clock, and stress calculations were performed for each point. Differences between the models of fragment removal and internal fixation were compared. Table 1 shows the standard deviation, 50th percentile, and range (maximum and minimum) values of the stress in the two groups. The mean stress values in the fragment removal and internal fixation groups were 16.94 and 14.17 MPa, respectively (P = 0.027). Stress tests were also performed on 50 distinct points along the fracture line, which were selected randomly from a cloud distribution stress diagram. Results were analyzed by the

Kruskal-Wallis test. Table 2 reports the mean, standard deviation, 50^{th} percentile, and range (maximum and minimum) values of the stress in the two groups. The mean values of stress in the fragment removal and internal fixation groups were 25.41 and 19.45 MPa, respectively ($P = 0.002$).

Discussion

Patient outcomes after femoral head injuries need to be improved. Considerable controversy exists regarding treatment protocols for these injuries. There is insufficient data to support treatment by fragment excision versus internal fixation.[11-15] Most orthopedic surgeons treat only a few cases in their professional careers, and data on the best treatment could improve patient outcomes. Fractures of the femoral head are of interest because they are frequently accompanied by additional complications, such as avascular necrosis and posttraumatic osteoarthritis.[5,16]

FE is a convenient and effective method for biomechanical research under normal and pathological conditions.[17,18] Mechanical behaviors of biological systems can be understood more accurately and sensitively with modeling due to precise control over the experimental design.[19] There are many FE models of femoral head injuries and biomechanical studies on femoral load transfer and distribution.

In this study, we compared two different operative treatments for Pipkin type I femoral head fractures using FE analyses. 3D models were built, and stress changes were detected under defined loads. To our knowledge, this is the first FE model of a Pipkin type I fracture and the first treatment comparison study using biomechanical methods. Stress differences between the two treatment groups occurred along the fracture line. Stress distribution maps showed that stresses were greater and more concentrated in the fragment removal group compared to the internal fixation group. For type I femoral head fractures, stresses on the femoral head were distributed relatively uniformly in the internal fixation group, which may help maintain correct anatomic structures. In contrast, the concentration of stress on the femoral head in the fragment removal group may increase the risk of severe complications, including femoral head necrosis and traumatic arthritis.[20-23]

Our biomechanical results are consistent with other clinical studies,[4-5] which achieved positive results after internal fixation. Prokop *et al*.[5] treated 9 patients with Pipkin type I fractures, using biodegradable polylactide pins for internal fixation. They obtained positive results and few adverse reactions 54.2 months after the procedures. Henle treated 12 patients with digastric trochanteric osteotomies, and removed fragments accurately under direct visual inspection. Patients were monitored for 2 to 96 months, and the outcomes were favorable.[4] Retrospective analyses of the 12 patients showed long-term good or excellent results in 10 patients (83.3%). Although other factors, such as age, sex, and time between injury and treatment, may influence the outcomes of femoral head fracture, our findings suggest that the different stresses and stress distributions may be one biomechanical explanation for the different results of the treatment approaches.

There are some limitations of our model. First, the size of the fragment, shape, site of fracture, and location of the pins were not taken into account. Second, individual differences in collodiaphyseal angles or anteversion angles were not considered. We also did not include the effects of articular cartilage, which may influence the FE results. In addition, the material characteristics of the cortical and cancellate bone were not considered, and the interface of the bone and the screw was set to infinity. We used 4 times the body weight as the force of hip joint loading. This approximation was made according to the results of Bergmann[24] and Davy,[25] which showed that hip joint loading during normal walking is 1 to 4 times the body weight. In addition, we considered Johnston's results, which revealed that median peak forces during walking are approximately 4 times the body weight.[26] We assumed that the direction of the force was vertical and did not consider horizontal compressive forces.[27-28]

Finally, the numerical model was constructed on the basis of data from one normal hip. Individual differences in gender, age, ethnicity, underlying pathologies, and activity level were not considered. For computational biomechanics, a very important restriction is the ability to model a population, with most studies using either a single or small set of bone models and extrapolating their findings.[29] The sample size is too small to perform meaningful statistical analysis on the results obtained in this study. Hence, these results need to be validated in a larger subject population size, which we plan to do next.

Taken together, this is the first time that FE modeling has been used to study the stress changes with different treatments for Pipkin I fractures. Our model data indicate that stresses on the femoral head are different after treatment by fragment removal or internal fixation. The stress was greater and more concentrated in the femoral head after fragment removal. This finding may improve our biomechanical understanding of the treatments and may help surgeons in making appropriate treatment plans for this type of injury. Further experimental and clinical studies should be undertaken to confirm the results generated by the FE model.

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Figure Legends

Figure 1. Reconstruction of a 3D numerical model of a healthy femoral head.

A) Transmission of CT data to MIMICS software. B) Bone was extracted based on gray scale. C) Femoral head was extracted. D) 3D numerical femoral head reconstruction after meshing by ABAQUS.

Figure 2. Reconstruction of a 3D numerical model of a Pipkin type I femoral head fracture.

A) A 3D sphere was used to cut the 3D femoral head based on a Pipkin type I femoral head. B) Intersection was set at the fragment. C) Lateral view of the fragment. D) Portion remaining distal to the fracture.

Figure 3. Reconstruction of a 3D numerical screw model.

A) Screw model reconstructed by Solidworks Software. B) Screw model after remeshing by MIMICS.

Figure 4. Reconstruction of implantation.

A) Implanted points of the screws on the fragment. B) Implanted points of the screws on the remaining femoral head. C) Implantation of screws on the fragment. D) Implantation of the fragment on the femoral head.

Figure 5. Stress distribution after removal of the fragment.

Table 1. S. Mises stress after loading on fixed points.

Group	*N*	Mean (MPa)	Std Dev (MPa)	50th Percentile (MPa)	Minimum (MPa)	Maximum (MPa)
Fragment removal	13	16.94	16.79	9.02	2.36	46.81
Internal fixation	13	14.17	14.08	7.60	1.45	39.89

(Paired T test, *P=0. 0266, The difference is statistically significant, P* < 0.05 SAS software)

Table 2. S. Mises stress after loading on random points.

Group	*N*	Mean (MPa)	Std Dev (MPa)	50th Percentile (MPa)	Minimum (MPa)	Maximum (MPa)
Fragment removal	50	25.41	12.12	23.24	5.86	63.82
Internal fixation	50	19.45	14.62	14.64	3.00	62.71

(Kruskal-Wallis Test, $P=0.0024$, *The difference is statistically significant*, $P < 0.05$ SAS software)

Figure 1

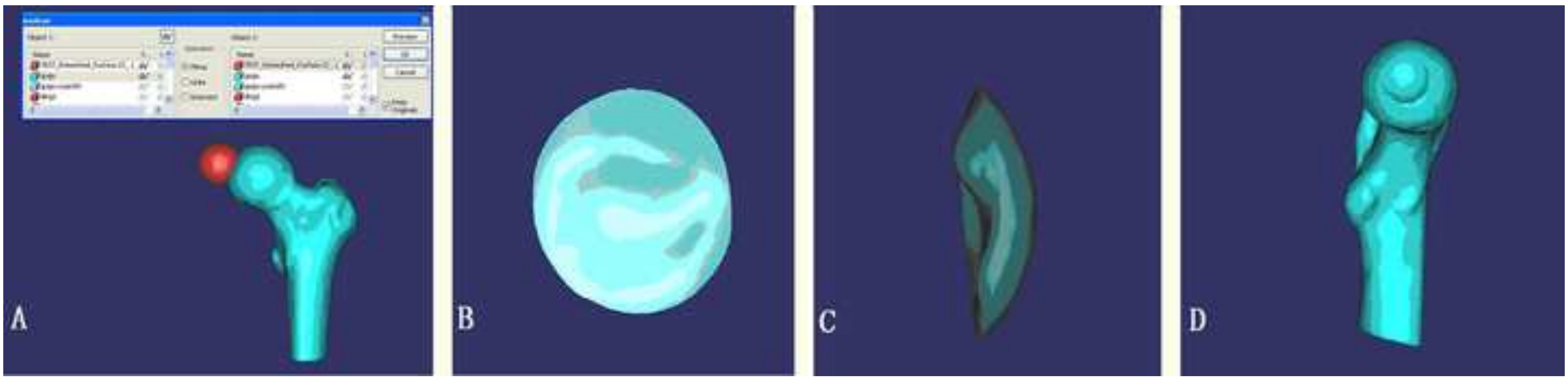

Figure 2

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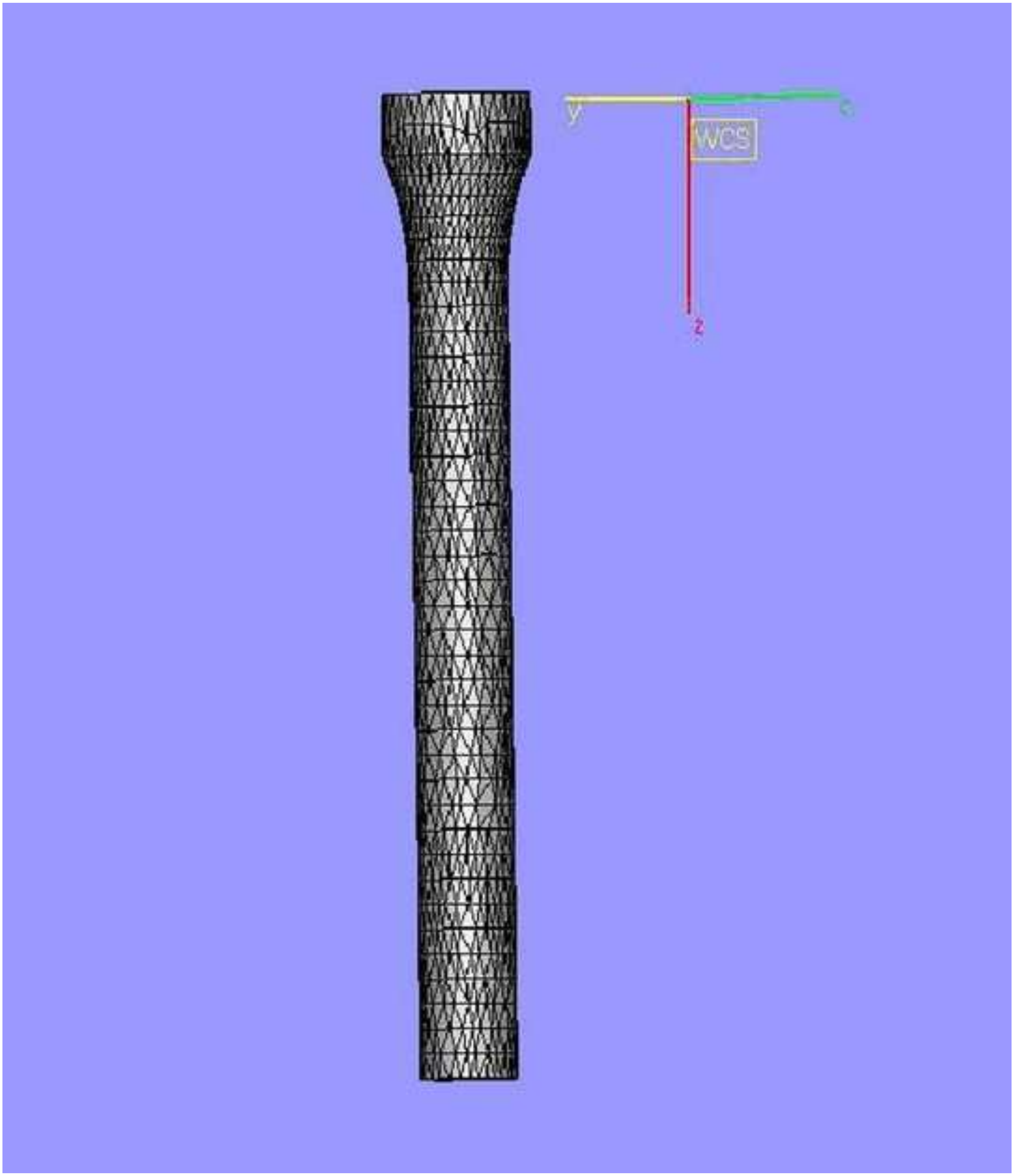

Figure 3

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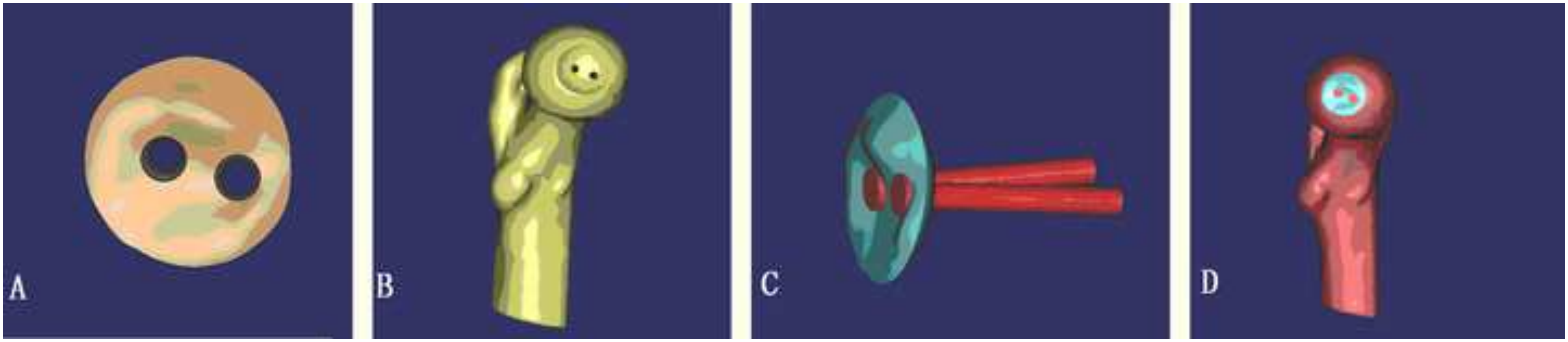

Figure 4

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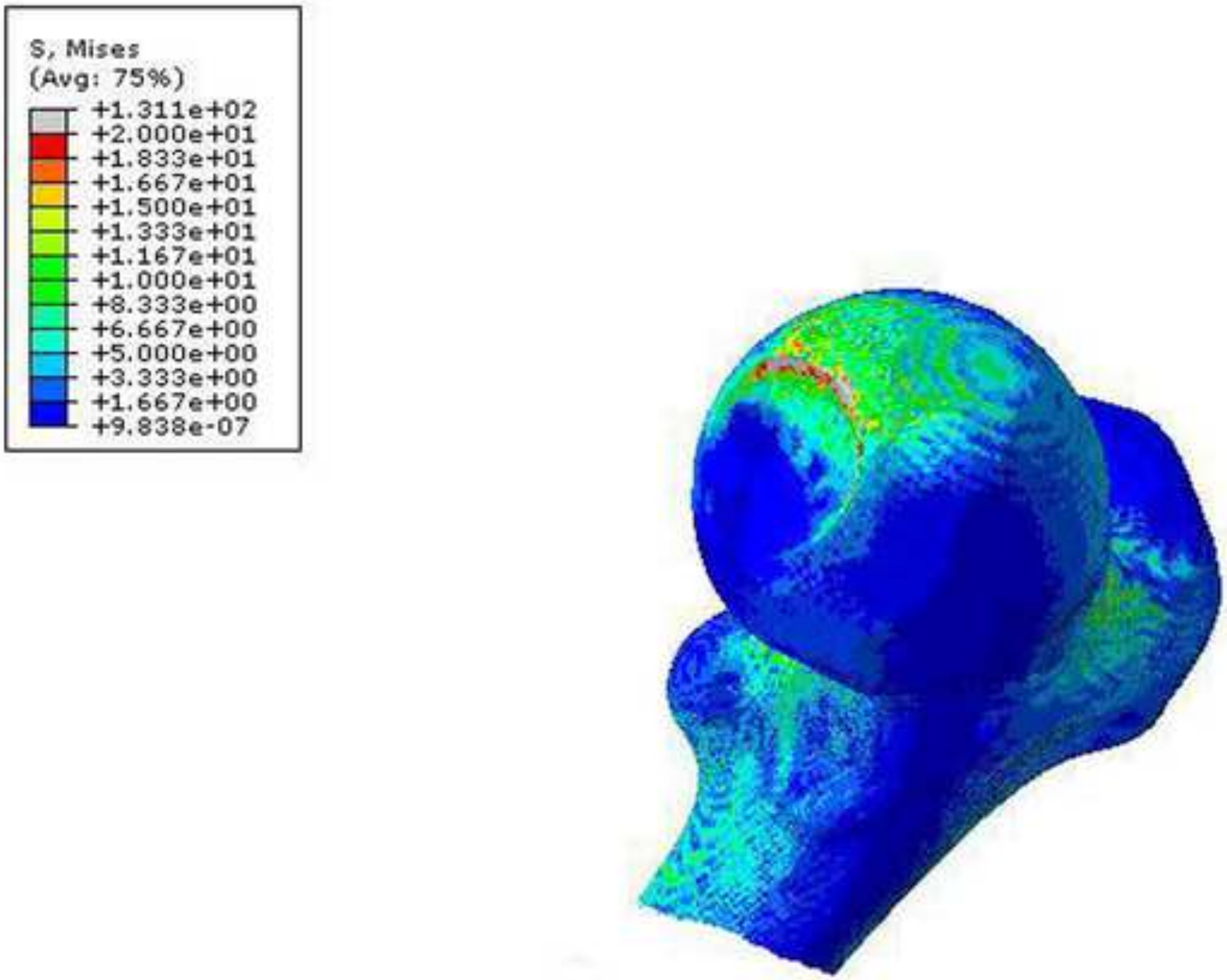

Figure 5

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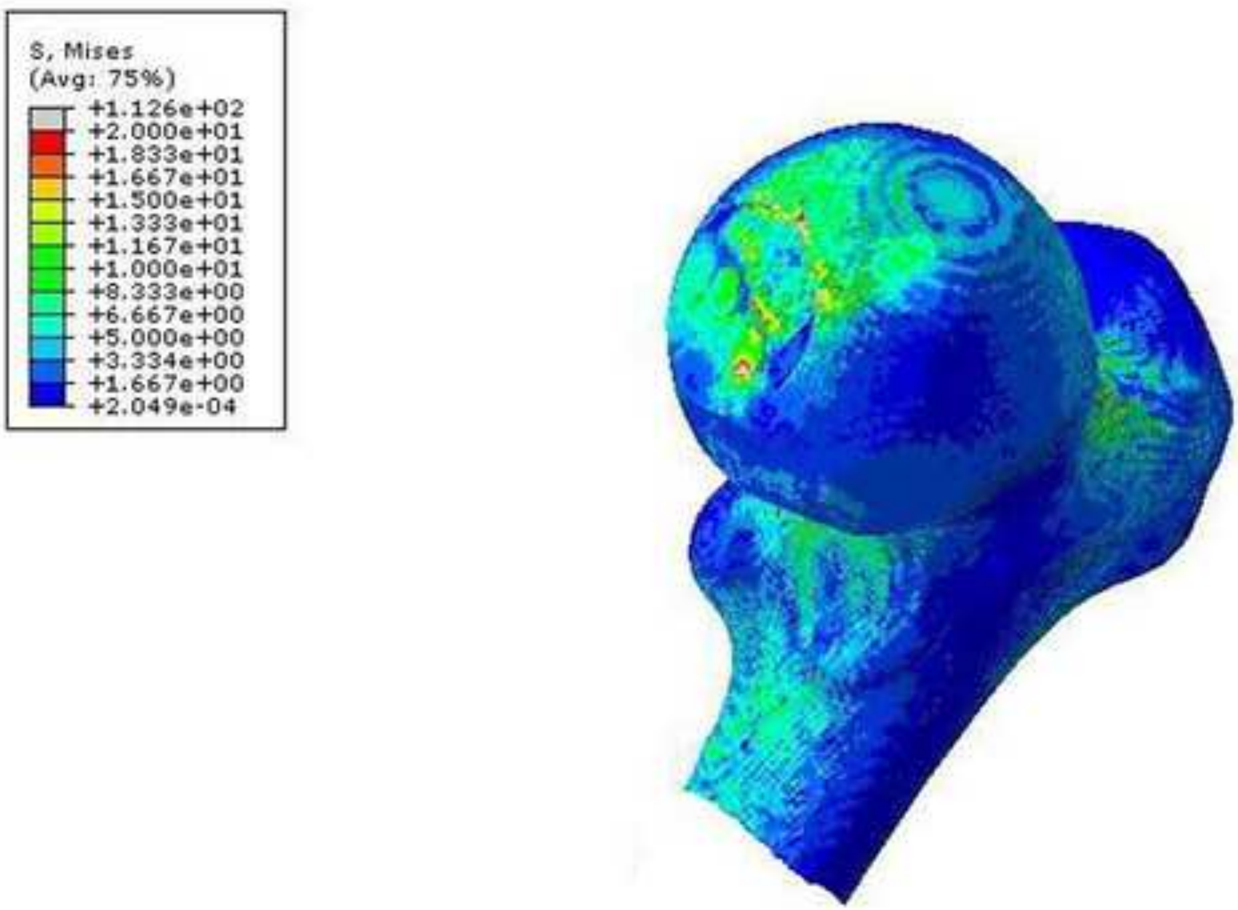

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