# Allograft Fibula Combined with Cannulated Screw for Femoral Head Necrosis: A Finite Element Analysis

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# Abstract

**Background:** Osteonecrosis of femoral head (ONFH) is characterized by high incidence and disability. Allograft fibula combined with cannulated screw has been extensively applied for treating Osteonecrosis of femoral head. However, its biomechanical outcomes remain unclear. The present study aimed to investigate the optimal placement of the allograft fibula and cannulated screw for treating ONFH.

**Methods:** Two types (C1 and C2) of NONFH finite element models were built based on a healthy subject and the Japanese Investigation Committee (JIC) classification system. The allograft fibula combined with cannulated screw was simulated in the respective type of the model. Different models were built by complying with the different positions of allograft fibula and cannulated screw (below model, posteriorly below model, anteriorly below model and anteriorly above model). Furthermore, a comparison was drawn on the maximum stress value and the mean stress value of the subchondral cortical bone of femoral head weight-bearing area.

**Results:** As indicated from the finite element analysis, normal femoral head, necrotic femoral head and postoperative femoral head achieved the different maximum stress values, and the maximum stress value achieved by necrotic femoral head significantly reached over that of normal femoral head. After the operation, the maximum stress value of subchondral cortical bone in the weight-bearing area of the femoral head was noticeably down-regulated compared with that before the operation (necrotic femoral head). When the cannulated screw was directly below the fibula, subchondral cortical bone in the weight bearing area of femoral head achieved the smallest maximum stress value and average stress value, which showed a statistical difference from those of other models ($P<0.05$).

**Conclusion:** Allograft fibula combined with cannulated screw is capable of significantly reducing the stress of subchondral cortical bone in the weight-bearing area of the ONFH femoral head, as well as down-regulating the stress concentration in the ONFH weight-bearing area. For JIC C1 and C2 osteonecrosis of the femoral head, when administrated with allograft fibula combined with cannulated screw, the optimal biomechanics was the cannulated screw located just directly below the fibula.


# Introduction

Osteonecrosis of the femoral head (ONFH) refers to a common orthopedic disease, which acts as a painful and disabling condition that affects adolescents and adults [1, 2]. The necrosis of the femoral head is recognized as a slowly developing and progressive disease, which usually progresses to hip osteoarthritis without clinical intervention, thereby causing hip pain and loss of hip function [3]. Existing treatments for necrosis of the femoral head consist of physical therapy, drug therapy, hip preservation surgery, as well as joint replacement therapy. However, early total hip arthroplasty (THA) treatment may pose the risk of multiple revision as impacted by the tendency of younger ONFH onset, thereby seriously affecting the physical and mental health of patients and imposing the rising economic burden on patients [4, 5]. Accordingly, hip preservation surgery acts as the first choice for the early necrosis of the femoral head [6]. As revealed from existing studies, if active and effective surgical intervention was not performed before the collapse of the femoral head in patients, most patients will have the collapse of the femoral head in 2–3 years [7].

Numerous femoral head-preserving procedures have been available, consisting of osteotomy [6],core decompression [8], allogeneic bone compression and bone grafting [9], vascular bone flap implantation[10] and non/free-vascularized bone grafting [11]. To be specific, the treatment of early necrosis of femoral head with allograft fibula combined with cannulated screw has aroused rising attention[12].However, a wide range of studies have reported different success rates of Allograft Fibula for treating femoral head necrosis[13, 14]. As reported from an existing study, the success of Allograft Fibula for treating femoral head necrosis is related to duration of pain, age, Association Research Circulation Osseous (ARCO) and Japanese Osteonecrosis Investigation Committee (JIC) classifications[15].Furthermore, several studies indicated that different placements of the cannulated screw will impact the stress transmission of the femoral head[16]. For this reason, this study hypothesized that different allograft fibula and cannulated screw positions will impact the stress on the surface of the femoral head, probably affecting the effect of allograft fibula for treating ONFH. In the present study, the CT data were adopted to reconstruct the Osteonecrosis of the femoral head model, and the relationship between allograft fibula and cannulated screw was analyzed with finite element method to investigate the optimal placement of the implant. Hopefully, this study can provide theoretical and mechanical reference for the clinical treatment of Osteonecrosis of the femoral head with Allograft fibula combined with cannulated screw.

## Methods

# General Information

This study selected a 26-year-old male patient exhibiting a body weight of 70kg and a height of 172cm. In addition, CT spiral scan data of the hip of the patient were acquired. The thickness and spacing of the layer reached 0.5mm and 5mm, respectively. Furthermore, the resolution of each layer was 1024×1024 pixels, and the images generated were stored as DICOM format.

# Analysis software

On the whole, Mimics software (version 16.0, Materialise NV, Leuven, Belgium), Geomagic-Studio software (version 11.0, Geomagic Corporation, USA), Solidworks software (version 2014, Dassault Systems S.A, USA) and Abaqus 6.10.1 (Simulia, Rhode Island, USA) were applied in this study as the analysis software.

# Establish the model of ONFH

The DICOM CT data were imported into the Mimiucs software. The appropriate threshold segmentation was selected. The redundant connections between different bone cortex were deleted, the femoral cortical bone outline was obtained. Subsequently, regional growth, skin editor, cavity filling of cortical bone repair were conducted, and then a 3D model of cortical bone was built. After the mild smooth surface treatment, a STL format file was exported (Fig. 1). The STL file was imported into the Geomagic-Studio 11 software to conduct further surface smoothing, model peeling removal, mesh division, contour detection, curved surface construction and fitting, which was saved as STP format. Next, the STP format file was imported into the SoildWorks software for the assembly, and then the normal femoral head model was built. Afterwards, in accordance with the JIC classification, the 3D model of Osteonecrosis of the femoral head (JIC C1 and C2) were built.

# Establish the model of allograft fibula and cannulated screw

The finite element model of allograft fibula was built in the SoildWorks software. Cortical bone, which was 100mm in length, 10mm in outer diameter and 5mm in diameter, of the hollow part was set up to implant allogeneic fibula column, and the model was saved as a PRT file. The finite element model of the cannulated screw was built in the SoildWorks software, and various specifications of the cannulated screw were set (e.g., length of 80mm, 90mm and 100mm). The hollow part had the diameter of overall 6.5mm, the diameter of the hollow part was all 5mm, and the thread length was 30mm, which was located at the distal end of the screw. Furthermore, the model was saved as PRT format (Fig. 2).

# Establish the model of allograft fibula combined with cannulated screw for ONFH

The JIC type C1 and C2 ONFH model, allograft fibula and cannulated screw were assembled with the SoildWorks 2015 software. The allograft fibula was implanted at 15mm below the crest of the greater trochanter at the necrotic area of the anterolateral column of the femoral head. Besides, the depth was lower than 5mm from the subchondral bone of the femoral head, as well as nearly 5mm from the lateral femoral neck cortex. By using the allograft fibula implantation model, the cannulated screws were placed directly below, posteriorly below, anteriorly below and anteriorly above the allograft fibula, respectively. Moreover, the insertion depth of the cannulated screws, no less than 5mm, did not exceed the depth of the allograft fibula. 8 allograft fibulae combined with cannulated screw models were respectively generated (JIC C1 below model, JIC C1 posteriorly below model, JIC C1 anteriorly below model, JIC C1 anteriorly above model, JIC C2 below model, JIC C2 posteriorly below model, JIC C2 anteriorly below model, as well as JIC C2 anteriorly above model), which were saved as an X_T file (Fig. 3).

# Material properties and meshing

The models were respectively imported into Abaqus software, and the proximal femur material acted as the isotropic elastic material. Table 1 lists the elastic modulus and Poisson's ratio of the respective material [17-20]. The femur, the cannulated screw and the fibula were all administrated with 10-node 4-hedral elements (C3D10), and Table 2 lists the nodes and elements of the respective model.

Table 1

Elastic modulus and Poisson's ratio of different materials

| Material | Elastic modulus（MPa） | Poisson's ratio |
|---|---|---|
| Femoral cortical bone | 15100 | 0.3 |
| Femoral cancellous bone | 445 | 0.22 |
| Cannulated screw | 110000 | 0.3 |
| Allograft fibula | 15100 | 0.3 |
| The necrotic bone | 125 | 0.15 |
| Cartilage | 10.5 | 0.45 |

Table 2

Nodes and units of each model (number)

| Groups | Femoral cortical bone | Femoral cancellous bone | Allograft fibula | Cannulated screw | The necrotic bone of JIC C1 | The necrotic bone of JIC C2 | Cartilage |
|---|---|---|---|---|---|---|---|
| Number of nodes | 145124 | 171453 | 10578 | 6957 | 35775 | 38784 | 22089 |
| Unit number | 86359 | 118008 | 6109 | 3495 | 24409 | 26480 | 11064 |

# Boundary conditions and loads

All nodes were constrained at the distal end of the femur of 6 degrees freedom to zero. The simplified model of standing on one foot was employed, and the axial stress of 700N, which was axial downward, was applied in the bearing area of the femoral head (Fig. 4). The relationship between the allograft fibula and the femoral bone was set as the friction, and the coefficient of friction reached 0.2. Furthermore, the relationship between the cannulated screw and the femoral bone was set as the binding relation.

# Evaluation criteria

First, the von Mises stress distribution of the subchondral cortical bone of femoral head was observed. Second, a comparison was drawn on the maximum stress value and mean stress value of the subchondral cortical bone of femoral head weight-bearing area.

# Statistical analysis

Stata 13.0 statistical software was employed for the statistical analysis, and χ2 test or Fisher's exact probability method was adopted to count the data. The measurement data were expressed as mean ± standard deviation (x±s), and the normal distribution (Shapiro-Wilk) and the homogeneity of variance test (Bartlett method) were performed simultaneously. Under the normal distribution and the homogeneous variance, Bonferroni method will be applied to draw the pairwise comparison. Furthermore, under the unnormal distribution, or the uneven variance, non-parametric test would be performed, and $P<0.05$ was statistically significant.

## Results

# Stress changes of the subchondral cortical bone of femoral head in normal, ONFH and ONFH postoperative weight-bearing area of femoral head

As indicated from the finite element analysis, different maximum stress values of subchondral cortex bone were reported in the bearing zone of normal femoral head, necrotic femoral head and postoperative femoral head. Necrotic femoral head achieved the maximum stress 31.09% higher than that of normal femoral head. Subchondral cortical bone in the weight-bearing area of femoral head after the operation achieved the maximum stress 14.81% lower than that before the operation. Moreover, as proven from the comparison of the cloud images, the bone stress in the subchondral cortex of the necrotic femoral head bearing area was more concentrated (Fig. 5). The maximum displacement values of the three groups of models were all identified in the force-bearing area above the femoral head, and the values tended to decrease from the inside to the outside of the greater trochanter area, from top to bottom.

Fig. 5 Stress nephogram of normal, ONFH, and ONFH postoperative subchondral cortical bone in the weight-bearing area of the femoral head. A: The maximum stress of subchondral cortex in the normal bearing area of femoral head reached 15.53MPa. B: The maximum stress of subchondral cortex bone in the bearing area of necrotic femoral head was 20.29MPa. C: The weight-bearing area of femoral head after the operation achieved the maximum stress of subchondral cortex bone as 18.78MPa.

## Stress variations of the subchondral cortical bone of femoral head in the JIC type C1 ONFH model

The identical 10 stress points were extracted from the maximum stress of subchondral cortex bone in the bearing area of femoral head of the respective JIC type C1 ONFH model, and the stress value was measured. As indicated from the results, all allograft fibula combined with cannulated screw postoperative models could effectively down-regulate the stress value of subchondral cortex in the weight-bearing area of femoral head, and a statistical difference was identified compared with the model of osteonecrosis of the femoral head alone ($P<0.05$). The subchondral cortex bone in the model with the cannulated screw located just below the allograft fibula achieved the lowest maximum and average stress values, which showed a statistical difference from that of other models ($P<0.05$) (Fig. 6, Table 3).

Fig. 6: Bone stress nephogram of the subchondral cortical bone of femoral head in the JIC type C1 ONFH model. A: JIC C1 ONFH model. B: JIC C1 below model. C: JIC C1 posteriorly below model. D: JIC C1 anteriorly below model. E: JIC C1 anteriorly above model. F: Comparison of average stress values of different JIC type C2 models. *Compared with the JIC C1 ONFH model, the difference in mean stress values of subchondral cortical bone showed statistical significance (p□0.05).▲As compared with the JIC C1 below model, the difference in mean stress values of subchondral cortical bone was statistically significant (p□0.05).

### Table 3

### Maximum and mean stress values of subchondral cortical bone in the weight-bearing zone of the JIC type C1 ONFH model (MPa)

| Groups | JIC C1 ONFH model | JIC C1 below model | JIC C1 posteriorly below model | JIC C1 anteriorly below model | JIC C1 anteriorly above model |
|---|---|---|---|---|---|
| Maximum stress value | 20.29 | 17.73 | 19.08 | 18.95 | 18.90 |
| Mean stress value(MPa) | 18.49±0.77 | 13.38±0.88* | 15.63±0.46*▲ | 15.51±0.75*▲ | 15.78±0.73*▲ |

*Compared with the JIC C1 ONFH model, the difference in mean stress values of subchondral cortical bone showed statistical significance (p□0.05).▲In comparison with the JIC C1 below model, the difference in mean stress values of subchondral cortical bone was statistically significant (p□0.05).

## Stress changes of the subchondral cortical bone of femoral head in the JIC type C2 ONFH model

The identical 10 stress points were extracted from the maximum stress of subchondral cortex bone in the bearing area of femoral head of each JIC type C2 ONFH model, and the stress value was measured. As suggested from the results, the subchondral cortex in the weight-bearing area of the femoral head necrosis model achieved the higher average stress value than that of all allograft fibula combined with cannulated screw postoperative models, and the difference showed statistical significance ($P<0.05$). The average stress values of the subchondral cortex bone in the model with the cannulated screw located just below the allograft fibula reached the lowest, statistical difference was reported compared with other models ($P<0.05$) (Fig. 7, Table 4). The average stress values of all JIC type C2 ONFH models reached over the corresponding JIC type C1ONFH models, and the difference was statistically insignificant ($P>0.05$).

Fig. 7: Bone stress nephogram of the subchondral cortical bone of femoral head in the JIC type C2 ONFH model. A: JIC C2 ONFH model. B: JIC C2 below model. C: JIC C2 posteriorly below model. D: JIC C2 anteriorly below model. E: JIC C2 anteriorly above model. F: Comparison of average stress values of different JIC type C2 models. *Compared with the JIC C2 ONFH model, the difference in mean stress values of subchondral cortical bone was statistically significant (p<0.05).▲In comparison with the JIC C2 below group, the difference in mean stress values of subchondral cortical bone showed statistical significance (p<0.05).

Table 4

Maximum and mean stress values of subchondral cortical bone in the weight-bearing zone of the JIC type C2 ONFH model (MPa)

| Groups | JIC C2 ONFH model | JIC C2 below model | JIC C2 posteriorly below model | JIC C2 anteriorly below model | JIC C2 anteriorly above model |
|---|---|---|---|---|---|
| Maximum stress value | 20.53 | 18.78 | 19.21 | 18.93 | 19.14 |
| Mean stress value | 18.84±0.82 | 14.58±0.81* | 16.48±0.74*▲ | 16.31±0.64*▲ | 16.81±0.79*▲ |

*Compared with the JIC C2 ONFH model, the difference in mean stress values of subchondral cortical bone showed statistical significance (p<0.05).▲In comparison with the JIC C2 below model, the difference in mean stress values of subchondral cortical bone was statistically significant (p<0.05).

# Discussion

Allograft fibula combined with cannulated screw has been considered a common treatment of ONFH, characterized by simple operation, low cost and quick recovery with high short-term efficacy as opposed to other procedures [21]. It is easy to promote in primary hospitals. However, the efficacy of this surgical methods has acted as a moot point for insufficient biomechanical evidences to support its precise efficacy [22]. In this study, a 3D finite element analysis was conducted to build an individualized 3D finite element model of ONFH based on CT imaging data of the patients. After the pre- and post-operative biomechanical data of the subchondral cortical bone of femoral head in patients with ONFH and varus deformity were collected and analyzed, allograft fibula combined with cannulated screw was found to be capable of effectively down-regulating the stress values of JIC C1 and C2 ONFH. The optimal biomechanics is that the cannulated screw are located directly under the fibula.

The collapse of the femoral head indicates the poor prognosis of ONFH. As indicated from the occurrence of the collapse, the normal structure of the hip joint has been destroyed. As the disease progresses further, artificial total hip replacement should be commonly conducted [23]. The collapse of the femoral head is primarily attributed to the decrease in the ability of the necrotic zone to bear stress. At the repair stage after femoral head necrosis, abnormal variations of the tissue structure occurred in the trabecular bone of the lesion. New bone and necrotic bone cannot bear the identical intensity of load as normal tissue [24]. For the mentioned reason, when stress is encountered, the normal area and the necrotic area cannot share the load in a balanced manner. A difference is identified in elastic modulus around the necrosis, so stress conduction dislocation occurs. Since the necrotic zone with reduced strength fails to conduct stress normally, the imbalance of stress bearing is concentrated in the local area. Stress concentration causes mild fracture of trabecular bone. The collapse occurs as impacted by the continuous action of stress [25]. As indicated from this study, stress concentration occurred in the weight-bearing area of femoral head necrosis, and the maximum stress in the weight-bearing area was elevated, as compared with those in healthy femoral heads. As revealed from existing studies [26], the surgical allograft fibula combined with cannulated screw is capable of reconstructing the ONFH load conduction path. When the fibula is implanted, the load of the femoral head will be transmitted to the femoral moment, which up-regulates the stress concentration of the subchondral bone and the stress shielding of the femoral head, and thus prevents the femoral head from collapsing. As suggested from this study, the postoperative stress declined significantly by measuring the subchondral stress, thereby demonstrating that the mechanics of the proximal femur after the allograft fibula combined with cannulated screw was reconstructed. According to Cao et al. [27], vascularized fibular grafting exhibited higher efficacy for treating osteonecrosis of the femoral head as compared with simple decompression. The mechanical and biological characteristics of the fibula help stimulate bone and vascular regeneration, provide strong mechanical support, partially restore the internal mechanical conduction of the femoral head, and provide sufficient time and space for the repair of new bone and alter the unstable state of the femoral head. For the femoral head without collapse, the collapse of the femoral head can be prevented. Furthermore, for the femoral head that has appeared mild collapse, allograft fibula combined with cannulated screw can partially correct the collapse and prevent the further occurrence of collapse.

As impacted by the existence of the femoral neck shaft angle, pressure, tension and shear force are generated at the proximal end of the femur when the body undergoes force transmission. The proximal femur adapts to the force to derive structures (e.g., tension trabecular bone, pressure trabecular bone, as well as femoral calcar). The load transferred from the body to the proximal femur is transferred to the cortical bone of the upper femur through structures such as trabecular bone [28]. As suggested by Filipov et al. [29], different screw positions exert different therapeutic effects on femoral neck fractures. Moreover, this result was confirmed by Lin et al. [16] with finite element method. Accordingly, this study speculates that the position of the screw and the fibula will undergo different mechanical variations in ONFH. The average stress of the weight-bearing area, reflecting its collapse risk, could be the critical measure here. As indicated from this study, for JIC C1 and C2 ONFH, when the cannulated screw is located directly below the fibula, the maximum and average stress values of the subchondral cortical bone in the weight-bearing area of the femoral head reach the smallest. This result may be explained as the screw is close to the lower part of the fibula, which can more effectively fix the fibula allograft by squeezing the cannulated screw. Moreover, when the cannulated screw is located just directly below the fibula, the fibula and the screw are capable of better transmit the stress of the hip joint. The allogeneic fibula should be implanted in the femoral head necrosis zone, which is commonly located on the anterolateral side of the femoral head, with a depth of 5 mm from the subchondral cortex. If the screw tip enters the subchondral necrosis area, a local stress concentration will be caused, and the cartilage will be more seriously damaged.

Several limitations were revealed in this study. First, the CT data were acquired from healthy femoral heads, instead of from collapsed femoral heads of osteonecrosis. Moreover, the hip model details were simplified, and the impacts from surrounding muscles were ignored. Lastly, multiple factors of graft survival were not considered (e.g., the accuracy of surgery, the occurrence of revascularization, as well as an imbalance in creeping substitution). In-depth studies are required to determine the clinical operation effect of allograft fibula combined with cannulated screw.

# Conclusion

Allograft fibula combined with cannulated screw is capable of significantly reducing the stress of subchondral cortical bone in the weight-bearing area of the ONFH femoral head, as well as down-regulating the stress concentration in the ONFH weight-bearing area. For JIC C1 and C2 osteonecrosis of the femoral head, when administrated with allograft fibula combined with cannulated screw, the optimal biomechanics was the cannulated screw located just directly below the fibula.

# Abbreviations

ONFH:osteonecrosis of femoral head, THA:total hip arthroplasty,CT:computed tomography,ARCO:Association Research Circulation Osseous,JIC:Japanese Osteonecrosis Investigation

Committee, DICOM: Digital imaging and communications in medicine.

## Declarations

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# Availability of data and materials

All the data will be available upon motivated request to the corresponding author of the present paper.

# Author Contributions

G.Z. was responsible for the design and implementation of the study presented. G.Z. and M.L. were responsible for the development of the finite-element models,G.Z., and T.Y.L. conducted the experiments and were responsible for the acquisition of the data. B.L, H.Z.Sand J.L.X. prepared the initial draft of the manuscript. B.F.W.gave critical feedback during the study and critically revised the submitted manuscript for important ntellectual content. All authors have read and approved the final manuscript to be submitted.

# Ethical approval

This study was conducted in agreement with the Declaration of Helsinki and its later amendments or comparable ethical standards and had been approved by the ethics board of The First Affiliated Hospital of Guangzhou University of Chinese Medicine (No: Y[2019]118).

# Consent for publication

Not applicable

# Competing interests

The authors declare no competing interests.

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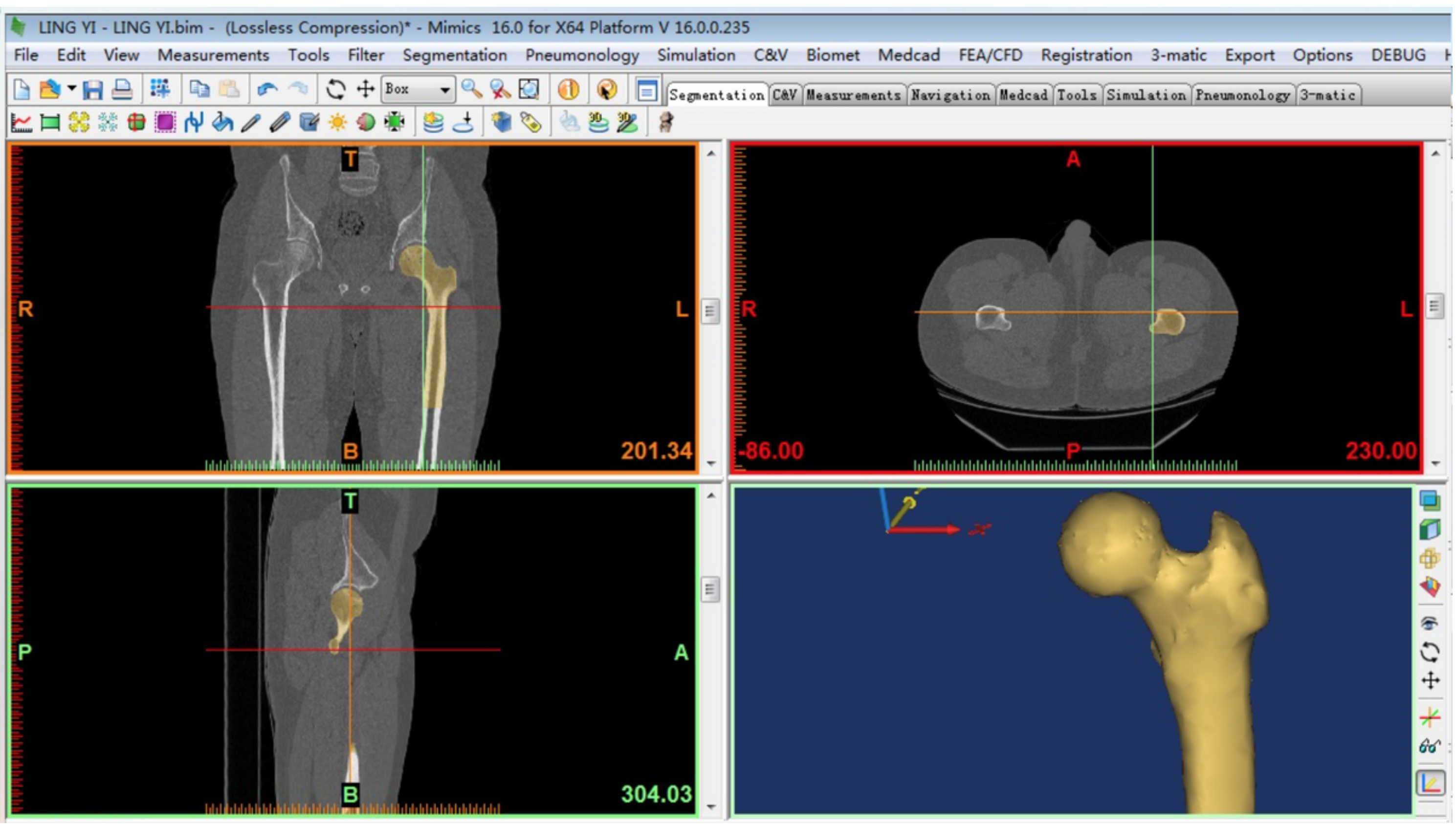
# Figures




## Figure 1

Mimiucs software was used to build a 3D model of hip cortical bone

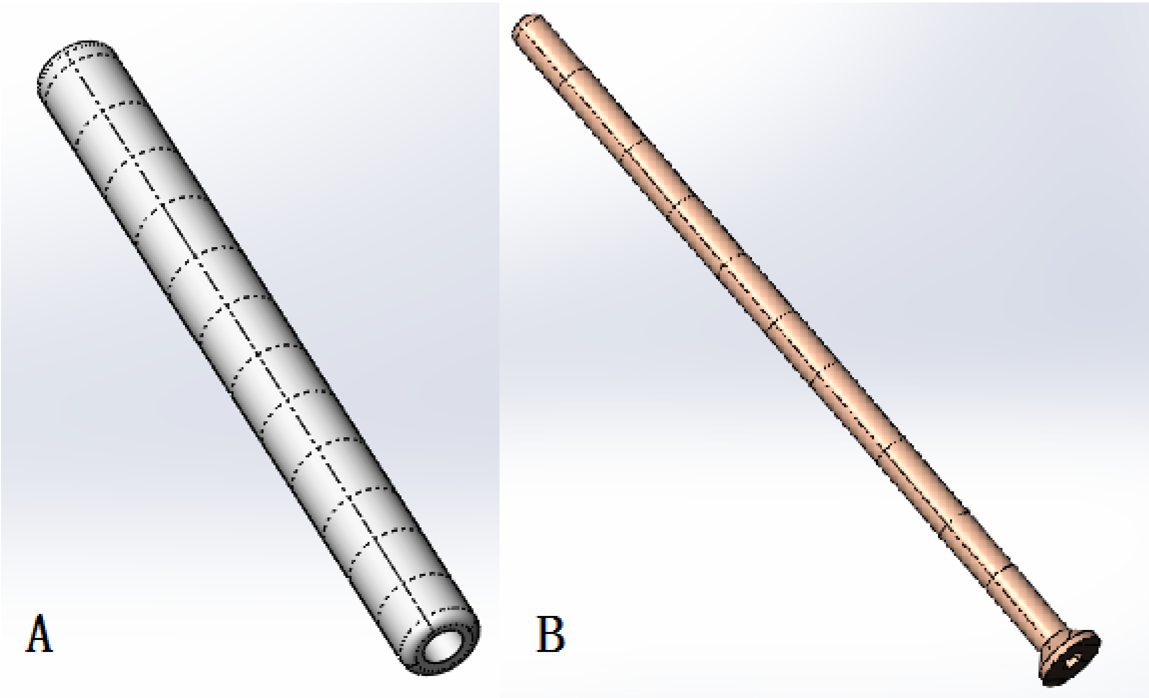



**Figure 2**

Model of allograft fibula and cannulated screw

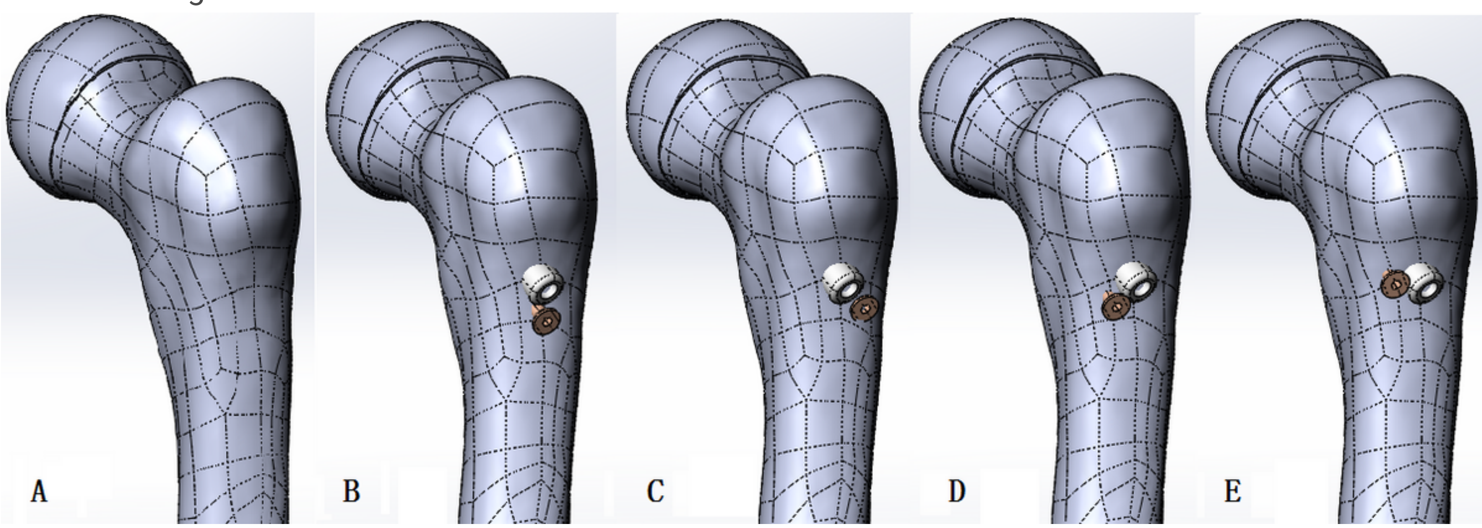



**Figure 3**

Femoral head necrosis hip joint model. A: ONFH model. B: Below group. C: Posteriorly below group. D: Anteriorly below group. E: Anteriorly above group.

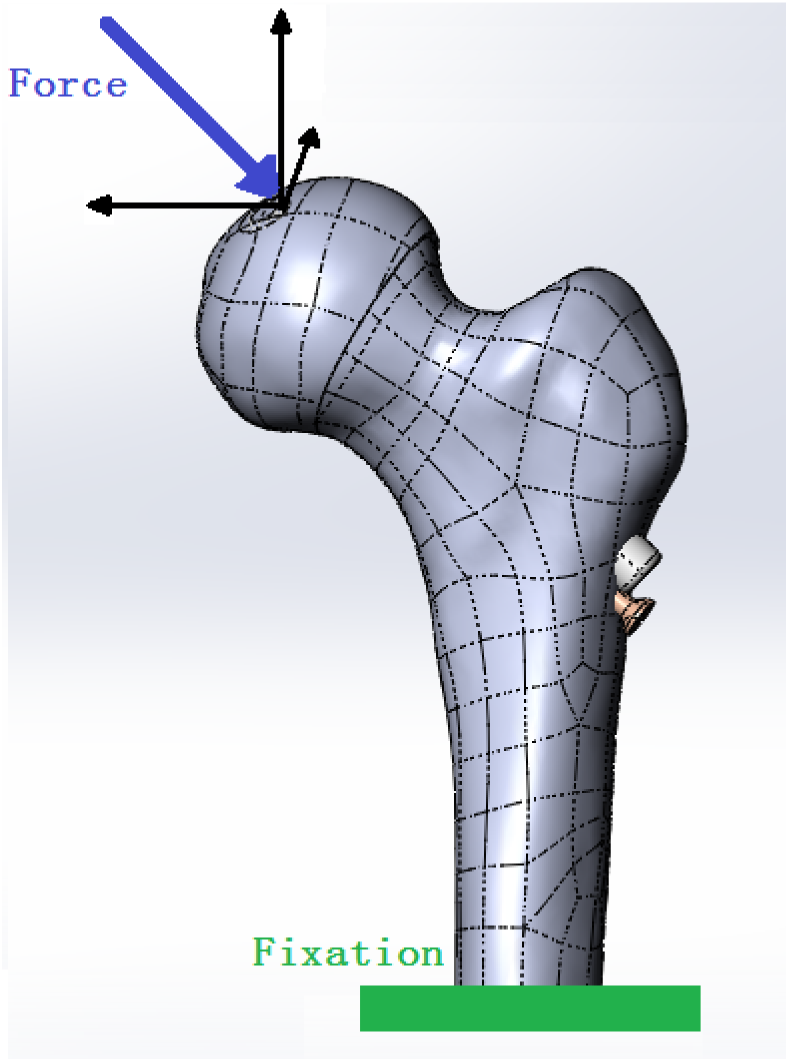



**Figure 4**

Set the boundary conditions and load

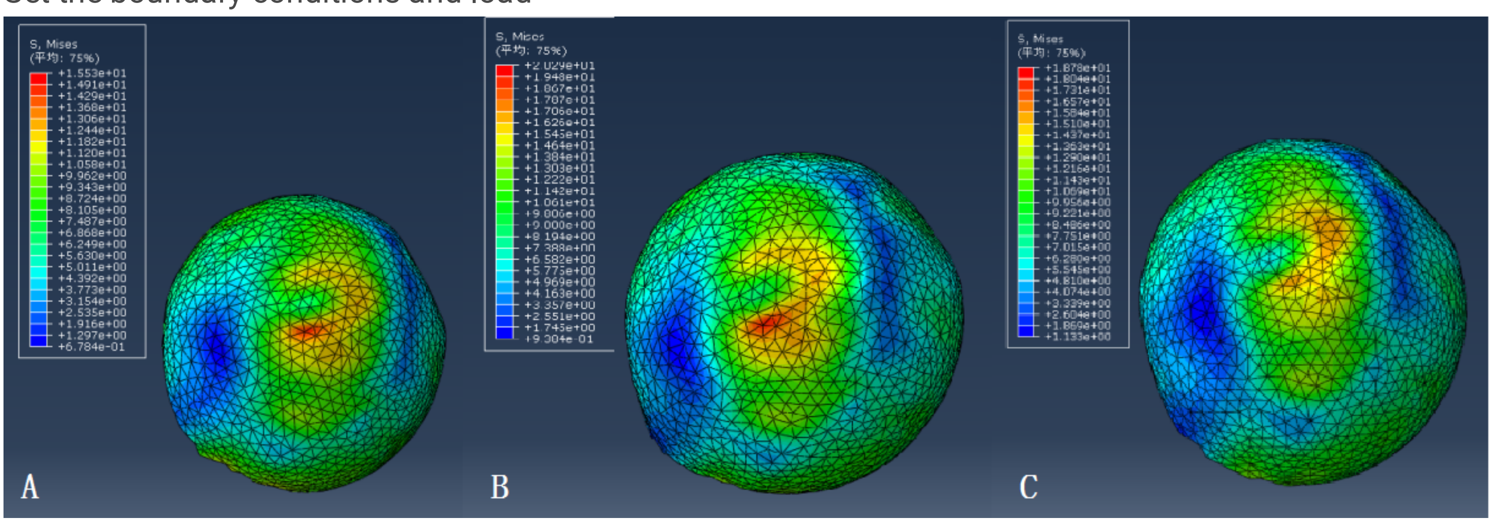
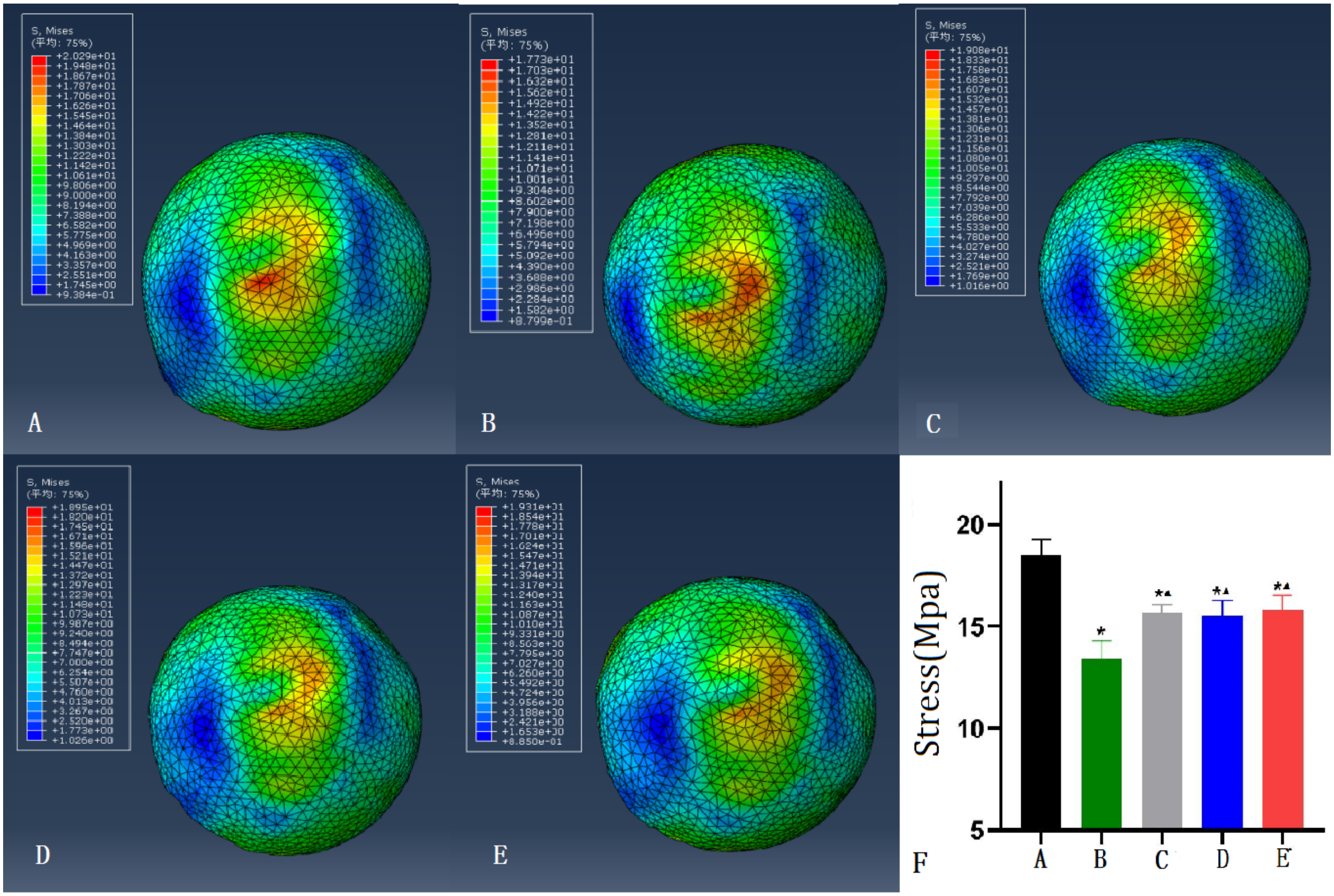


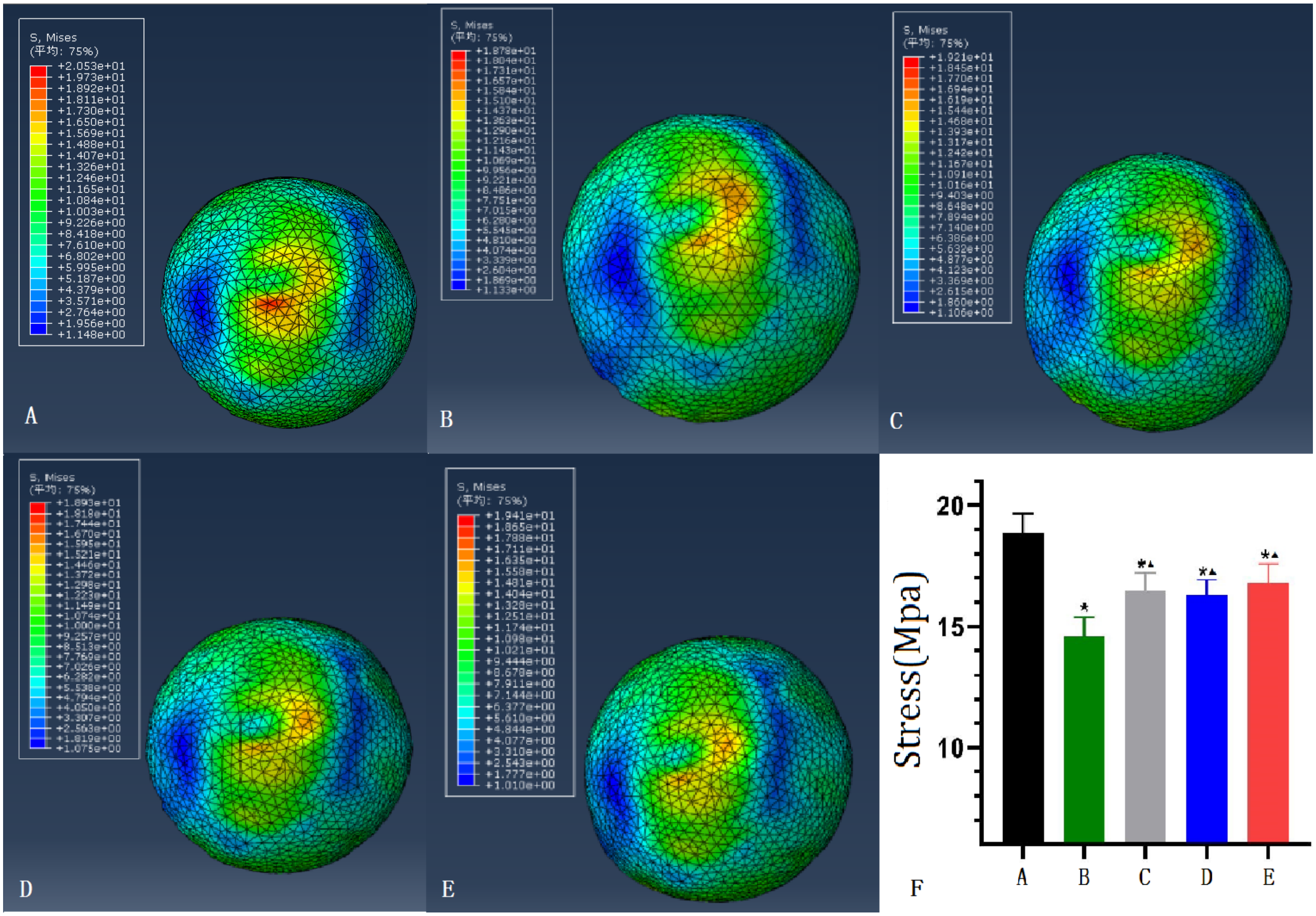

**Figure 5**

Stress nephogram of normal, ONFH, and ONFH postoperative subchondral cortical bone in the weight-bearing area of the femoral head. A: The maximum stress of subchondral cortex in the normal bearing area of femoral head reached 15.53MPa. B: The maximum stress of subchondral cortex bone in the bearing area of necrotic femoral head was 20.29MPa. C: The weight-bearing area of femoral head after the operation achieved the maximum stress of subchondral cortex bone as 18.78MPa.




## Figure 6

Bone stress nephogram of the subchondral cortical bone of femoral head in the JIC type C1 ONFH model. A: JIC C1 ONFH model. B: JIC C1 below model. C: JIC C1 posteriorly below model. D: JIC C1 anteriorly below model. E: JIC C1 anteriorly above model. F: Comparison of average stress values of different JIC type C2 models. *Compared with the JIC C1 ONFH model, the difference in mean stress values of subchondral cortical bone showed statistical significance (p0.05).▲As compared with the JIC C1 below model, the difference in mean stress values of subchondral cortical bone was statistically significant (p 0.05).




## Figure 7

Bone stress nephogram of the subchondral cortical bone of femoral head in the JIC type C2 ONFH model. A: JIC C2 ONFH model. B: JIC C2 below model. C: JIC C2 posteriorly below model. D: JIC C2 anteriorly below model. E: JIC C2 anteriorly above model. F: Comparison of average stress values of different JIC type C2 models. *Compared with the JIC C2 ONFH model, the difference in mean stress values of subchondral cortical bone was statistically significant ($p<0.05$).▲In comparison with the JIC C2 below group, the difference in mean stress values of subchondral cortical bone showed statistical significance ($p<0.05$).