

Three-Dimensional Finite Element Biomechanical Study of Surgical Dislocation with Impacted Bone Grafting for Osteonecrosis of the Femoral Head

Yuan Chen

Department of Orthopedics, Bijie Traditional Chinese Medicine Hospital, Bijie, Guizhou, 551700, China

Zeng Li (Corresponding Author)

Department of Orthopedics, Bijie Traditional Chinese Medicine Hospital, Bijie, Guizhou, 551700, China

Email: gylizeng@aliyun.com

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Abstract

Objective: To evaluate the biomechanical effects of surgical dislocation combined with impacted bone grafting for osteonecrosis of the femoral head (ONFH) under varying hip flexion angles using three-dimensional finite element analysis, and to elucidate the mechanical rationale for restricting excessive hip flexion during postoperative rehabilitation. **Methods:** A 42-year-old male patient with unilateral ARCO stage II ONFH was enrolled. Based on CT imaging data, three three-dimensional finite element models were established: a normal hip (normal group), a necrotic hip (necrotic group), and a postoperative hip following surgical dislocation with impacted bone grafting (surgical group). Four loading conditions corresponding to hip flexion angles of 0°, 30°, 60°, and 90° were simulated, applying abductor muscle force of 300 N, iliopsoas muscle force of 188 N, vastus lateralis muscle force of 292 N, and hip joint reaction force of 700 N. The maximum Von Mises stress, maximum displacement, and stress distribution patterns of the femoral head and necrotic region were compared among the groups. **Results:** (1) For maximum femoral head stress, at 0° flexion, it was 5.36 MPa for the normal group, 11.75 MPa for the necrotic group, and 13.22 MPa for the surgical group; at 90° flexion, it was 8.74 MPa, 14.94 MPa, and 21.58 MPa, respectively. (2) Regarding maximum stress in the necrotic region, at 0° flexion, it was 0.512 MPa for the necrotic group and 0.448 MPa for the surgical group; at 90° flexion, it was 0.885 MPa and 0.874 MPa, respectively. (3) For maximum femoral head displacement, at 0° flexion, it was 0.453 mm (normal), 0.479 mm (necrotic), and 0.463 mm (surgical); at 90° flexion, it was 1.235 mm, 1.309 mm, and 1.245 mm, respectively. (4) In the surgical group, grafted bone displacement increased from 0.410 mm at 0° to 1.081 mm at 90°, and grafted bone stress increased from 14.50 MPa at 0° to 18.44 MPa at 90°. **Conclusion:** Surgical dislocation with impacted bone grafting can partially restore the mechanical environment of the necrotic femoral head. However, stress values in the surgical group remained higher than those in the normal group across all flexion angles, indicating that postoperative restricted weight-bearing is still necessary. Hip flexion angle significantly influences femoral head loading, and excessive hip flexion should be avoided in the early postoperative period to mitigate the risk of graft micromotion and subsequent femoral head collapse.

Keywords: Femur head necrosis; Surgical dislocation; Bone grafting; Finite element analysis; Biomechanics; Hip joint.

1. Introduction

Osteonecrosis of the femoral head (ONFH) is a debilitating condition characterized by the death of osteocytes and bone marrow components due to interruption of the blood supply to the femoral head, ultimately leading to structural bone changes and joint dysfunction. It predominantly affects young and middle-aged adults. Without timely and effective intervention, most cases progress to femoral head collapse within a few years, eventually necessitating total hip arthroplasty (THA) [1]. Epidemiological data indicate a prevalence of non-traumatic ONFH of approximately 0.725% in China, translating to an estimated 8.12 million affected individuals aged 15 years and older [1]. Further analysis by Tan et al. [2] based on the China ONFH database detailed patient characteristics and treatment patterns across the country. For young and middle-aged ONFH patients, while THA offers a definitive solution, the limited lifespan of prosthetic components often mandates revision surgeries if performed prematurely [3]. Ng et al. [4], analyzing nationwide data from the United States between 2010 and 2020, observed a rising trend in hip-preservation procedures among patients under 50, reflecting a growing clinical demand for joint-conserving strategies.

Current hip-preserving surgical options for ONFH primarily include core decompression, various bone grafting techniques, vascularized bone flap transplantation, and osteotomies [5, 6]. In 2001, Ganz et al. [7] introduced the surgical hip dislocation technique, which offers excellent visualization of the femoral head and acetabulum while preserving the blood supply to the medial femoral circumflex artery, making it an ideal approach for precise

management of femoral head lesions. Building upon this approach, the impacted bone grafting procedure involves debriding necrotic bone and subsequently implanting autologous cancellous bone or iliac crest bone grafts to reconstruct the mechanical support structure of the femoral head and promote bone repair. A retrospective study by [Chen et al. \[8\]](#) on adolescents and young adults undergoing surgical dislocation combined with bone grafting reported satisfactory outcomes in pre-collapse and early collapse cases. Moreover, [Zhou et al. \[9\]](#), in a mid-term follow-up of 64 patients (70 hips) who underwent this procedure, reported a Harris Hip Score excellent/good rate of 82.9% and a 5-year femoral head survival rate of 98.1%.

Three-dimensional finite element analysis (FEA) is an indispensable biomechanical tool for quantitatively evaluating the mechanical responses of skeletal structures and internal fixation systems under physiological loading [\[10, 11\]](#). [Zhang et al. \[12\]](#), through combined clinical and FEA studies, found that the presence and increasing diameter of cystic lesions within the necrotic area exacerbate the risk of femoral head collapse, with significant stress concentration detectable around the cystic cavities. Finite element simulations by [Tran et al. \[13\]](#) demonstrated that large necrotic lesions can increase peak stress within the femoral head by up to 186%, while core decompression with bone substitute filling effectively restores the normal mechanical environment of the articular cartilage. [Wen et al. \[14\]](#), using FEA based on the China-Japan Friendship Hospital (CJFH) classification, indicated that necrosis localized in the lateral pillar carries a higher risk of collapse, and high-angle hip flexion can lead to excessive deformation of the necrotic region.

To date, the mechanical response characteristics of the surgical dislocation with impacted bone grafting procedure under varying hip flexion angles lack systematic investigation. This study aims to establish three distinct finite element models (normal, necrotic, and postoperative) to simulate loading conditions at four flexion angles. The objectives are to quantify the improvement in the femoral head's mechanical environment conferred by this surgery and to elucidate the influence of hip flexion angle on postoperative femoral head stress and displacement, thereby providing a biomechanical foundation for postoperative rehabilitation guidelines.

2. Materials and Methods

2.1. Study Subject and Data Source

A 42-year-old male patient (height: 170 cm, weight: 62 kg) diagnosed with left-sided ARCO stage II ONFH at the Department of Orthopedics, Bijie Traditional Chinese Medicine Hospital, was enrolled. Exclusion criteria included acetabular dysplasia, previous hip surgery, and systemic metabolic bone diseases. Informed consent was obtained from the patient, and the study protocol was approved by the Ethics Committee of Bijie Traditional Chinese Medicine Hospital (Approval No. ky-2025-05).

Bilateral hip CT scans were performed using a 64-slice spiral CT scanner (GE, USA), covering from 1 cm above the iliac crest to 12 cm below the lesser trochanter. Scan parameters included a slice thickness of 0.625 mm. The acquired DICOM data were used to reconstruct three-dimensional geometric models of the healthy proximal femur, the pre-operative necrotic hip, and the post-operative hip (3-month follow-up).

2.2. Establishment of Three-Dimensional Finite Element Models

2.2.1. Three-Dimensional Geometric Model Reconstruction

DICOM data were imported into Mimics 21.0 software (Materialise, Belgium). Bone tissue was segmented based on Hounsfield Unit (HU) thresholds (HU > 226 defined as cortical bone, 130-226 as cancellous bone). Three-dimensional surface models of the femur and acetabulum were reconstructed. After smoothing and hole-filling, the models were exported in STL format. The STL files were then imported into Geomagic Wrap 2017 software (3D Systems, USA) for surface reconstruction, noise reduction, smoothing, and NURBS surface fitting to generate solid geometric models.

2.2.2. Model Grouping

Three three-dimensional finite element models were established: **Normal Group:** Based on the healthy contralateral hip, representing normal physiological conditions. **Necrotic Group:** Based on pre-operative data of the affected hip, featuring an ARCO stage II necrotic lesion in the anterolateral region, retaining the original morphology of the lesion. **Surgical Group:** Based on 1-month post-operative CT data, simulating the state after surgical dislocation with impacted bone grafting, including the autologous iliac bone graft implant.

2.2.3. Mesh Generation

The geometric models were imported into HyperMesh 14.0 software (Altair, USA) for mesh generation. Tetrahedral elements (C3D4) were employed, with distinct element properties assigned to cortical and cancellous bone. Local mesh refinement was applied to the necrotic zone, grafted area, and regions of anticipated stress concentration. Mesh convergence was assessed starting with a global element size of 2.0 mm, progressively refined to 1.5 mm and 1.0 mm. Convergence was deemed achieved when the change in calculated stress values between successive refinements was < 5% [\[15\]](#). Mesh information for each group is detailed in Table 1.

Table-1. Mesh Information for Each Model Group

Group	Number of Elements	Number of Nodes
Normal	~185,000	~268,000
Necrotic	~198,000	~287,000
Surgical	~238,000	~345,000

2.3. Material Property Assignment

Material parameters were assigned based on the literature [14, 16, 17, 15]. All structures were assumed to be homogeneous, isotropic, and linearly elastic materials. Specific parameters are presented in Table 2.

Table-2. Material Properties of the Models

Material Type	Cortical Bone	Cancellous Bone	Necrotic Bone	Graft Bone	Cartilage
Elastic Modulus (MPa)	17,000	700	350	800	10.5
Poisson's Ratio	0.30	0.30	0.30	0.30	0.45

2.4. Boundary Conditions and Loading

2.4.1. Boundary Constraints

Complete fixation constraints were applied to the acetabulum and pubic symphysis. A frictionless contact interface (coefficient of friction $\mu = 0.01$) was defined between the acetabular cartilage and the femoral head cartilage, permitting relative sliding, with transverse joint reaction forces considered negligible [15].

4.2. Loading Conditions

Muscle forces were applied according to the methodology described by Chen et al. [15]: abductor muscle force of 300 N ($\delta=20^\circ$, $\gamma=180^\circ$), iliopsoas muscle force of 188 N ($\delta=47^\circ$, $\gamma=262^\circ$), and vastus lateralis muscle force of 292 N ($\delta=180^\circ$, $\gamma=0^\circ$). A hip joint reaction force of 700 N was applied axially to the distal femur [3]. Loading was performed at four different hip flexion angles: 0° (standing), 30° (slight flexion), 60° (sitting), and 90° (squatting).

2.5. Finite Element Solution

The three model groups were imported into ANSYS Workbench 19.0 (ANSYS, USA) for static structural analysis. A sparse matrix direct solver was utilized to compute stress distribution, maximum Von Mises stress, and maximum displacement values for each model at the four specified flexion angles [15].

2.6. Primary Outcome Measures

- (1) Maximum Von Mises stress (MPa) of the entire femoral head.
- (2) Maximum Von Mises stress (MPa) in the necrotic/grafted region.
- (3) Maximum displacement (mm) of the entire femoral head.
- (4) Maximum displacement (mm) in the necrotic region.
- (5) Displacement and stress values for the grafted bone in the surgical group.
- (6) Stress distribution contour plots and load transfer pathways.

2.7. Statistical Analysis

As a finite element simulation study not involving random sampling or hypothesis testing, the results are presented as numerical values and contour plots, with descriptive comparative analysis [15].

3. Results

3.1. Model Validation

The stress distribution of the normal group at 0° flexion was compared with the literature [14, 15]. The peak femoral head stress in our model was 5.36 MPa, and the stress distribution pattern in the medial cortical region was consistent with previous reports, thereby validating the model.

3.2. Comparison of Maximum Femoral Head Stress

Maximum femoral head stress in all three groups increased progressively with increasing flexion angle. At 0° flexion, stress was 5.36 MPa (normal), 11.75 MPa (necrotic, +119.2% vs. normal), and 13.22 MPa (surgical, +12.5% vs. necrotic). At 30° , values were 6.49 MPa, 12.52 MPa (+92.9%), and 15.56 MPa (+24.3%). At 60° , values were 8.68 MPa, 14.46 MPa (+66.6%), and 19.97 MPa (+38.1%). At 90° , values were 8.74 MPa, 14.94 MPa

(+70.9%), and 21.58 MPa (+44.4%). The surgical group exhibited the highest femoral head stress among the three groups at all flexion angles, reaching a maximum of 21.58 MPa at 90° flexion, which was 146.9% higher than the normal group at the same angle. Detailed values are shown in Table 3, and stress contour maps are presented in Figures 1A-1C.

Table-3. Maximum Femoral Head Stress (MPa) at Different Flexion Angles

Group	0°	30°	60°	90°
Normal	5.36	6.49	8.68	8.74
Necrotic	11.75	12.52	14.46	14.94
Surgical	13.22	15.56	19.97	21.58

Figure-1A. Femoral head maximum stress contour maps for the Normal group at different flexion angles.

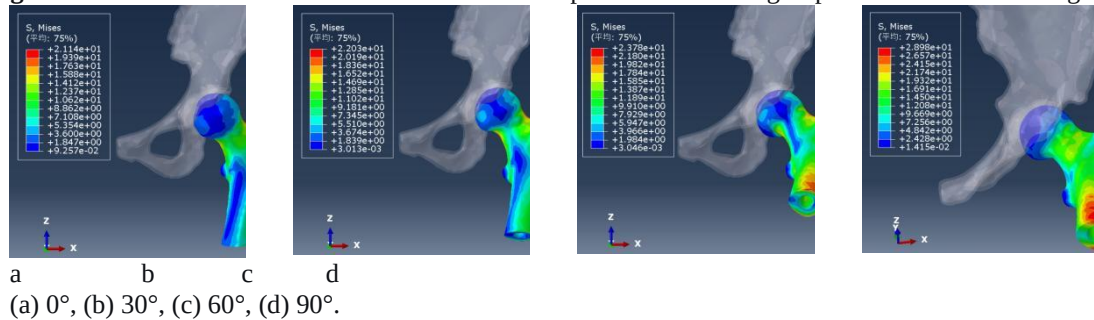


Figure-1B. Femoral head maximum stress contour maps for the Necrotic group at different flexion angles.

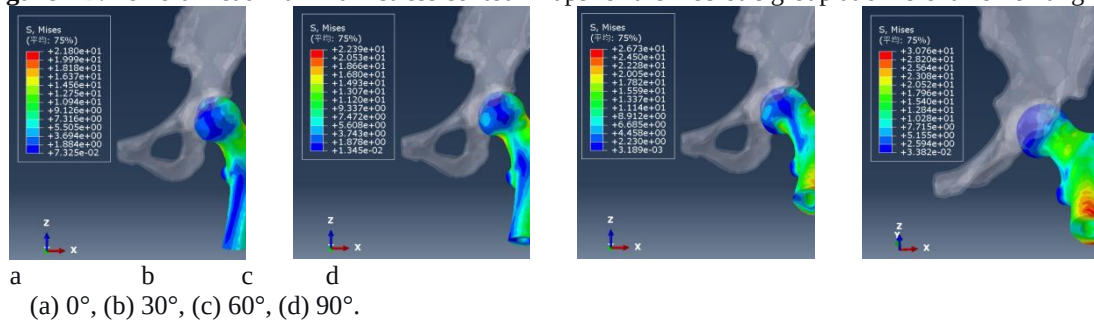
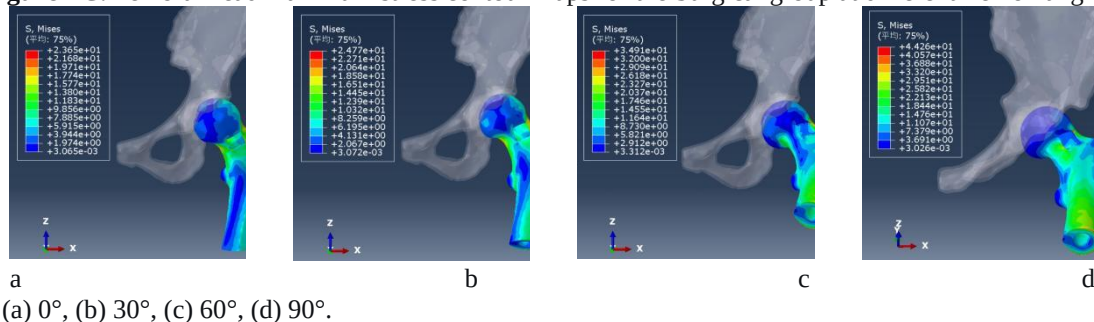


Figure-1C. Femoral head maximum stress contour maps for the Surgical group at different flexion angles.

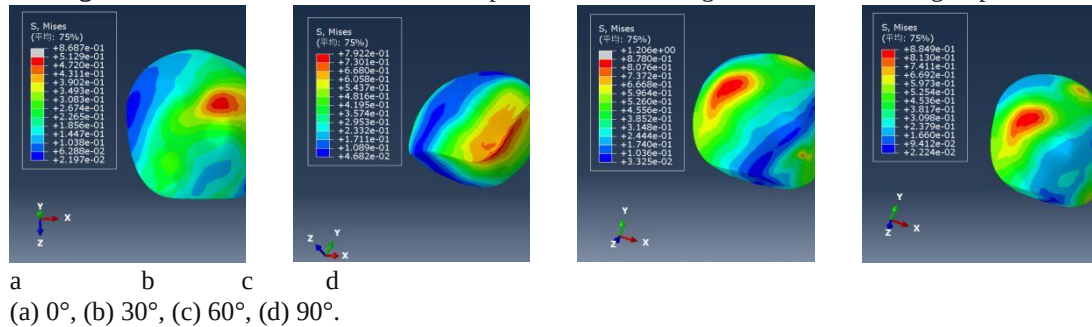
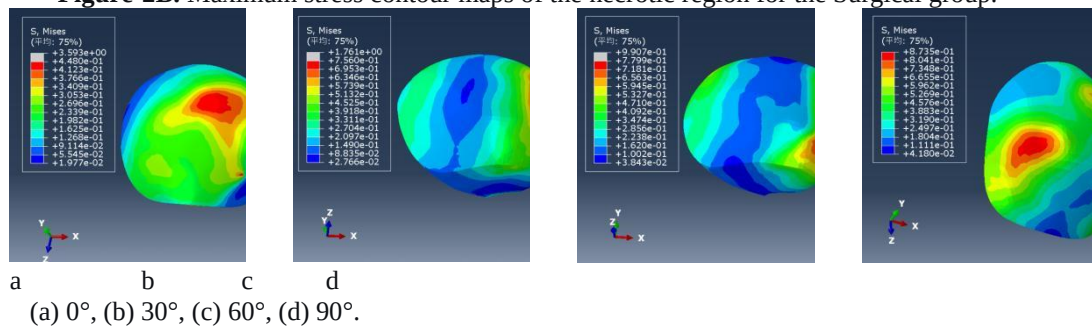


3.3. Comparison of Maximum Stress in the Necrotic Region

Maximum stress in the necrotic region increased with flexion angle in both groups. At 0° flexion, it was 0.512 MPa (necrotic) and 0.448 MPa (surgical), representing a 12.5% reduction in the surgical group. At 30°, values were 0.792 MPa and 0.756 MPa (-4.5%). At 60°, values were 0.878 MPa and 0.780 MPa (-11.2%). At 90°, values were 0.885 MPa and 0.874 MPa (-1.2%). The surgical group consistently showed lower maximum stress in the necrotic region compared to the necrotic group, with the greatest reduction observed at 0° (12.5%) and the least at 90° (1.2%). This suggests that impacted bone grafting provides a stress-sharing effect on the necrotic area, but this protective effect diminishes with increasing hip flexion. Data are detailed in Table 4 and contour maps in Figures 2A-2B.

Table-4. Comparison of Maximum Stress in the Necrotic Region (MPa)

Flexion Angle	0°	30°	60°	90°
Necrotic Group	0.512	0.792	0.878	0.885
Surgical Group	0.448	0.756	0.780	0.874

Figure-2A. Maximum stress contour maps of the necrotic region for the Necrotic group.**Figure-2B.** Maximum stress contour maps of the necrotic region for the Surgical group.

3.4. Displacement and Stress of the Grafted Bone in the Surgical Group

In the surgical group, grafted bone displacement increased consistently with flexion angle: 0.410 mm at 0°, 0.560 mm at 30° (+36.6%), 0.886 mm at 60° (+58.2% vs. 30°), and 1.081 mm at 90° (+22.0% vs. 60°). Displacement at 90° was 163.7% higher than at 0°. Regarding grafted bone stress, it was 14.50 MPa at 0°, 15.21 MPa at 30° (+4.9%), decreased to 13.56 MPa at 60° (-10.9%), and rose to 18.44 MPa at 90° (+36.0% vs. 60°). The transient decrease in graft stress at 60° may reflect a redistribution of load pathways at this specific angle. Details are in Table 5 and Figures 3A-3B.

Table-5. Displacement and Stress of Grafted Bone in the Surgical Group

Flexion Angle	0°	30°	60°	90°
Graft Displacement (mm)	0.410	0.560	0.886	1.081
Graft Stress (MPa)	14.50	15.21	13.56	18.44

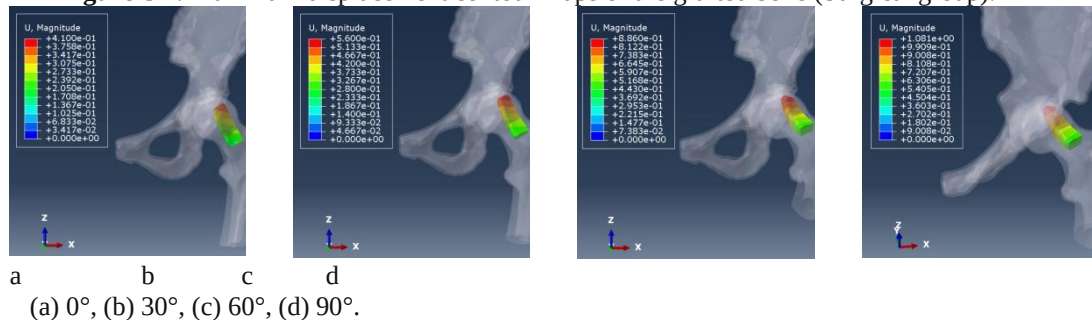
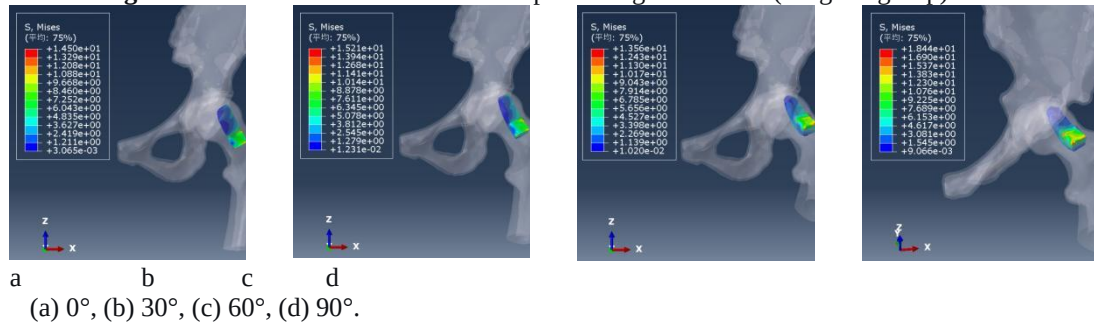
Figure-3A. Maximum displacement contour maps of the grafted bone (Surgical group).

Figure-3B. Maximum stress contour maps of the grafted bone (Surgical group).

3.5. Comparison of Maximum Femoral Head Displacement

Maximum femoral head displacement increased with flexion angle in all groups. At 0°, displacement was 0.453 mm (normal), 0.479 mm (necrotic, +5.7%), and 0.463 mm (surgical, -3.3% vs. necrotic), close to normal. At 30°, values were 0.619 mm, 0.647 mm (+4.5%), and 0.638 mm (-1.4%). At 60°, values were 1.004 mm, 1.078 mm (+7.4%), and 1.016 mm (-5.8%). At 90°, values were 1.235 mm, 1.309 mm (+6.0%), and 1.245 mm (-4.9%). The surgical group's displacement was consistently between the normal and necrotic groups and closer to the normal group. The displacement at 90° was approximately 2.7 times that at 0° for all groups (Normal: 2.73; Necrotic: 2.73; Surgical: 2.69). Values are shown in Table 6 and contour maps in Figures 4A-4C.

Table-6. Maximum Femoral Head Displacement (mm)

Group	0°	30°	60°	90°
Normal	0.453	0.619	1.004	1.235
Necrotic	0.479	0.647	1.078	1.309
Surgical	0.463	0.638	1.016	1.245

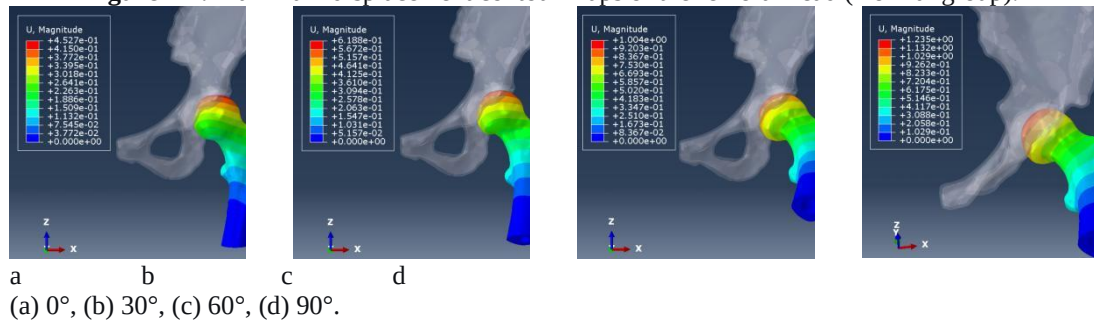
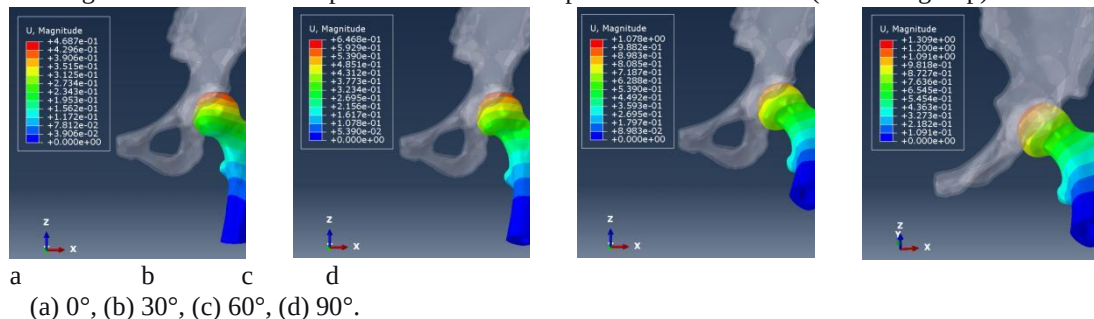
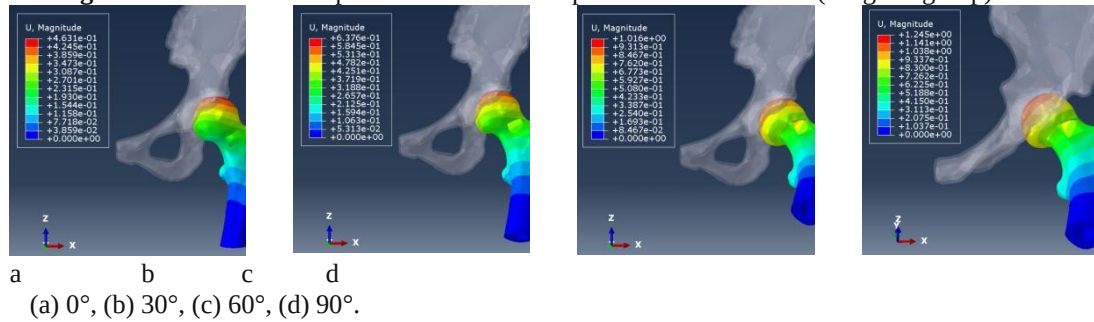
Figure-4A. Maximum displacement contour maps of the femoral head (Normal group).**Figure 4B.** Maximum displacement contour maps of the femoral head (Necrotic group).

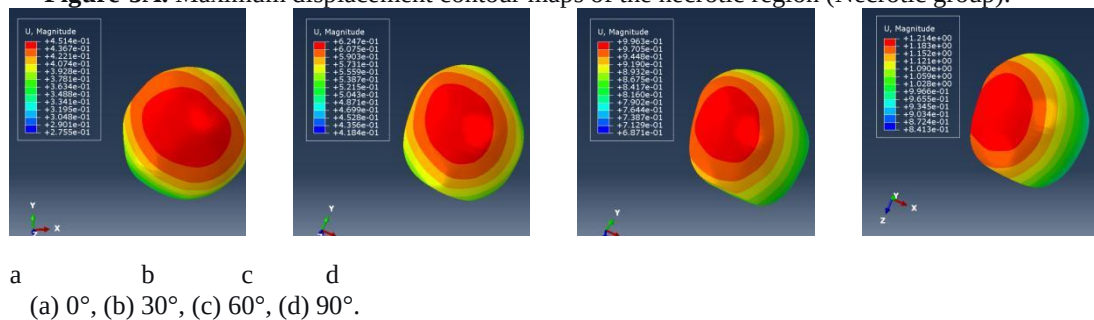
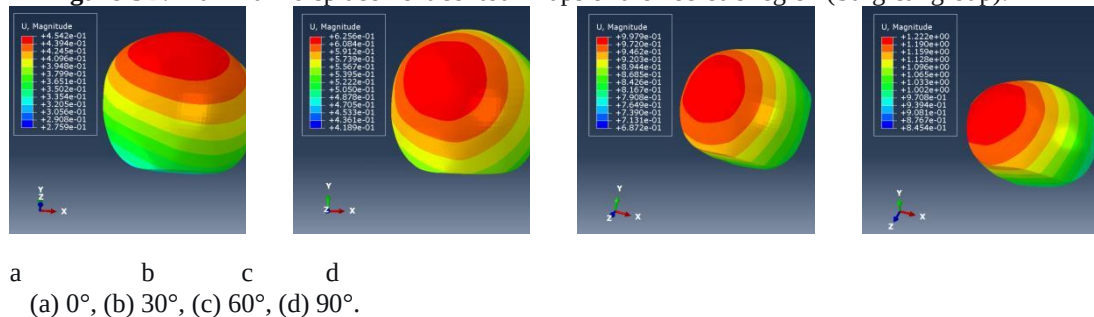
Figure-4C. Maximum displacement contour maps of the femoral head (Surgical group).

3.6. Comparison of Maximum Displacement in the Necrotic Region

Maximum displacement in the necrotic region increased with flexion angle. At 0°, it was 0.451 mm (necrotic) and 0.454 mm (surgical, +0.7%). At 30°, values were 0.625 mm and 0.626 mm (+0.2%). At 60°, values were 0.996 mm and 0.998 mm (+0.2%). At 90°, values were 1.121 mm (necrotic) and 1.222 mm (surgical, +9.0%). While displacements were comparable between groups from 0° to 60°, a notable increase (9.0%) was observed in the surgical group at 90°, suggesting potential relative displacement at the graft-host bone interface under extreme flexion. Data are in Table 7 and Figures 5A-5B.

Table-7. Maximum Displacement in the Necrotic Region (mm)

Flexion Angle	0°	30°	60°	90°
Necrotic Group	0.451	0.625	0.996	1.121
Surgical Group	0.454	0.626	0.998	1.222

Figure-5A. Maximum displacement contour maps of the necrotic region (Necrotic group).**Figure-5B.** Maximum displacement contour maps of the necrotic region (Surgical group).

4. Discussion

4.1. The Mechanism of Mechanical Degradation Following ONFH and the Pivotal Role of the Lateral Pillar

The fundamental driver of mechanical deterioration after ONFH lies in the mismatch between the mechanical properties of necrotic and healthy bone tissue. In our study, the elastic modulus of necrotic bone was set at 350 MPa [16], approximately half that of normal cancellous bone (700 MPa) [17]. This significant mechanical disparity inevitably leads to localized stress concentration under load. When these stresses exceed the fatigue strength of the bone, the collapse cascade initiates. Tran et al. [13] quantified this effect, showing that large necrotic areas can increase peak femoral head stress by up to 186%. Our findings are consistent with this, as the necrotic group exhibited significantly higher femoral head stress compared to the normal group at all angles, confirming the mechanical deterioration resulting from necrosis.

The critical role of the lateral pillar in maintaining femoral head resistance to collapse has been well-established. Bahk et al. [18], using propensity score-matched FEA models of 32 hips with ARCO stage 2 or 3

ONFH, found that non-collapsed hips tended to distribute stress across both the medial and lateral pillars, whereas collapsed hips showed stress concentration at the lateral pillar and the principal compressive trabeculae. They concluded that FEA-detected stress concentration in these areas could predict future collapse with high probability, emphasizing that "preserving the lateral pillar through hip-preserving surgery may be key to preventing further collapse" in young patients [18]. Similarly, Wen et al. [14] confirmed that when the necrotic lesion is located in the lateral pillar under identical loading and flexion conditions, the risk of collapse is higher. The lateral pillar cortex is recognized as a key biomechanical support structure of the femoral head. In our necrotic group, the lesion was situated in the anterolateral pillar, interrupting the normal load transfer path and resulting in a ring-shaped stress concentration around the necrotic periphery. This pattern aligns with the collapse-group stress characteristics described by Bahk et al. [18] and the biomechanical behavior of L2 and L3 types according to Wen et al. [14], further corroborating the essential structural role of the lateral pillar.

4.2. Biomechanical Evidence for Load Transfer Restoration via Impacted Bone Grafting

In the surgical group, the grafted bone, assigned properties similar to normal cancellous bone, restored the stress conduction function of the necrotic region. This allowed loads, which were previously borne predominantly by the peripheral sclerotic rim, to be redistributed and transmitted through the grafted area. The observed increase in grafted bone stress with flexion angle indicates that the graft consistently bore a portion of the femoral head load across the entire range of motion, confirming its continuous mechanical support role. Tran et al. [13] also noted that bone substitute filling can restore normal mechanical load pathways in the necrotic femoral head. The favorable mid-term clinical outcomes reported by Zhou et al. [9] (98.1% 5-year survival rate) provide clinical validation for the effectiveness of this approach in restoring mechanical integrity.

Intriguingly, the surgical group exhibited higher maximum femoral head stress than the necrotic group at all angles. This seemingly paradoxical result needs careful interpretation from a mechanical standpoint. In the necrotic group, the reduced elastic modulus of the necrotic tissue compromises its local load-bearing capacity, leading to stress concentration around the peripheral sclerotic rim; the overall peak femoral head stress appears relatively lower due to this stress redistribution. However, in the surgical group, the implanted graft restores the stress conduction capacity of the necrotic area. As a result, loads are effectively redistributed through the graft, manifesting biomechanically as an increase in the overall peak femoral head stress. This increase actually signifies the successful restoration of internal load transfer pathways within the femoral head, diverting stress away from the vulnerable sclerotic periphery. Zhang et al. [12], through combined clinical and FEA analysis, reported that cystic areas around the necrotic zone create stress concentrations and accelerate collapse, indirectly supporting the importance of restoring these pathways. Tran et al. [13] similarly emphasized that bone substitutes effectively restore the normal mechanical environment.

However, the fact that stress values in the surgical group remained consistently higher than in the normal group across all angles indicates that the mechanical properties of the reconstructed femoral head have not fully normalized. This discrepancy may stem from the still-lower elastic modulus of the graft compared to cortical bone and the intrinsic mechanical mismatch at the graft-host interface. Hong et al. [19] proposed that the anterolateral and combined preserved angles of the femoral head could guide patient selection for this procedure. They suggested that patients with a preoperative anterolateral preserved angle $>39.5^\circ$, lateral preserved angle $>46.5^\circ$, and combined preserved angle $>75.0^\circ$ are likely to achieve better surgical outcomes, highlighting the individual variability in post-grafting mechanical reconstruction.

4.3. Influence of Hip Flexion Angle on Femoral Head Loading: Comparisons and Extensions

A pivotal finding of our study is the significant, incremental effect of hip flexion angle on femoral head loading. The maximum femoral head displacement increased approximately 2.7-fold from 0° to 90° in all three groups. This aligns closely with Wen et al. [14], who, using FEA based on the CJFH classification, found that maximum deformation in their models increased progressively with hip flexion ($0^\circ \rightarrow 60^\circ \rightarrow 110^\circ$), with the L3 type showing deformation up to 1.8239 mm at 110° flexion. They specifically cautioned that "high-angle hip flexion easily leads to excessive deformation of the necrotic region; therefore, patients with ONFH should reduce or avoid high-angle hip flexion during weight-bearing training in the rehabilitation period."

Our study extends the work of Wen et al. [14] in two significant ways: First, we extend the analysis of flexion angle effects to postoperative models (post-impacted bone grafting), demonstrating that even after surgical reconstruction, high-angle flexion substantially increases mechanical loading. Second, by analyzing both overall femoral head and necrotic region displacements, we identified a clinically important finding: while necrotic region displacement was comparable between the surgical and necrotic groups from 0° to 60° flexion, at 90° flexion, it became notably larger in the surgical group. Concurrently, grafted bone displacement increased dramatically from 0° to 90° . This suggests that at high flexion angles, relative motion may occur at the graft-host interface. This complements Wen et al.'s work [14], which focused on deformation of the necrotic area itself, by providing new biomechanical evidence regarding the stability of the grafted bone.

4.4. Potential Risk and Clinical Implications of Graft Micromotion at High Flexion Angles

Bahk et al. [18] demonstrated that stress concentration at the lateral pillar and principal compressive trabeculae can serve as a high-probability predictor of future collapse. Our study further reveals that even after impacted bone

grafting, the graft faces a significant risk of displacement at high flexion angles, with necrotic region displacement at 90° exceeding that in the unoperated necrotic group. This suggests that while surgery restores stress conduction, the stability of the graft-host interface may be challenged under extreme flexion. Zhang et al. [12] showed that increasing cystic lesion diameter accelerates collapse, potentially linked to stress concentration and local micromotion. Our findings corroborate that, even after reconstruction, the graft remains susceptible to significant displacement at extreme flexion angles. In the early post-operative phase (e.g., 1-3 months), before biological osseointegration is complete, high-angle flexion could induce graft micromotion, potentially compromising bone healing [12].

Synthesizing our results with those of Wen et al. [14], we propose the following clinical recommendations: (1) **Restriction of Postoperative Flexion:** Given the substantial increase in femoral head and necrotic region loading, we recommend limiting hip flexion to under 30° for the first 4-6 weeks post-surgery. Flexion may be gradually increased to within 60° during weeks 6-12, and attempts at flexion exceeding 60° should be postponed until at least 3 months postoperatively. (2) **Avoidance of Graft Micromotion Risk:** Given the significant increase in graft displacement at high flexion angles, patients should avoid extreme flexion and torsional movements, particularly in the early post-operative period, to prevent graft loosening. (3) **Comprehensive Surgical Decision-Making:** Hong et al. [19] emphasized the importance of preoperative preserved angles for patient selection. Our mechanical data reinforce that for patients with extensive necrosis or severe lateral pillar involvement, even impacted bone grafting may not fully restore physiological mechanics and carries a higher risk of graft micromotion at high flexion angles, warranting careful consideration of surgical indications.

4.5. Study Limitations

This study has several limitations: (1) The model was based on a single individual, thus not accounting for variations in necrotic morphology or extent. (2) We assumed isotropic, linearly elastic material properties, which differ from the actual viscoelastic and anisotropic behavior of bone. (3) Only static loading conditions were analyzed; dynamic loads occurring during a gait cycle were not simulated [13]. (4) The post-operative model was based on 1-month CT data, which may not reflect the evolving mechanical environment following long-term osseointegration. Future studies should incorporate larger sample sizes with various necrosis types, use anisotropic material models and dynamic loading, and combine FEA with clinical follow-up to establish a quantitative relationship between mechanical parameters and patient outcomes.

5. Conclusion

Osteonecrosis of the femoral head leads to significantly elevated stress and displacement within the femoral head, disrupting the normal load transfer pathways and causing ring-shaped stress concentration around the necrotic periphery [14, 16]. Surgical dislocation with impacted bone grafting can restore the stress conduction function of the necrotic region. However, the overall femoral head stress in the surgical group remains higher than in the normal group, indicating the necessity for postoperative restricted weight-bearing. The bone graft provides localized mechanical protection to the necrotic area. Hip flexion angle is a critical determinant of femoral head loading. Given the substantial increase in graft displacement at high flexion angles, early postoperative rehabilitation should restrict flexion to under 60°, avoiding squatting movements to minimize the risk of graft micromotion and subsequent femoral head collapse.

Conflict of Interest: All authors declare no conflicts of interest.

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