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Original Article

Biomechanical evaluation with finite element analysis of the reconstruction of femoral tumor defects by using a double-barrel free vascularized fibular graft combined with a locking plate

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Abstract: The repair of large distal femoral tumor defects can be challenging for orthopedic surgeons. The combination of a double-barrel free vascularized fibular graft (DFVFG) with a locking plate is a viable option. However, the biomechanical influence of the fibular bone length on the locking plate attachment is unclear. We aimed to evaluate the stability of the distal femoral defect after reconstruction with fibular grafts of different lengths. A three-dimensional model of a healthy volunteer was developed using computed tomography images. A locking plate and bicortical screws were constructed and registered with CAD. Four models were defined (6 cm, 8 cm, 10 cm, and 12 cm bone grafts). The models were imported into finite element analysis software. Boundary-constrained and load conditions were applied. The model stress distribution and displacement were statistically analyzed. The Von Mises stress distributions were similar between the 6 cm, 8 cm, and 10 cm bone grafts and locking plate within each of those bone defect models ($P > 0.05$), while the Von Mises stress distribution was significantly higher in the 12 cm model than the other 3 lengths for both the bone graft and locking plate ($P < 0.05$). Significantly greater Von Mises stress was observed at the 12 cm bone graft and locking plate than with the shorter bone grafts. Therefore, we recommend that, to avoid complications, the bone graft should not exceed 12 cm when using FVFG in combination with a locking plate while treating a distal femoral tumor defect.

Keywords: Biomechanical evaluation, finite element, reconstruction of femoral tumor defects, double-barrel free vascularized fibular graft, locking plate

Introduction

Historically, tumors of the long bones that require resection of a portion of the bone often necessitated limb amputation. More recently, the use of allograft reconstruction, often in the form of an intercalary allograft or allograft arthrodesis, allows a greater rate of limb salvage for these patients. While the rate of limb salvage with allograft reconstruction has reached 80%, allograft reconstruction can be associated with substantial complications. The most common complications include nonunion, plate fracture, loosening of screws, and infection; these may be related to disturbances of the mechanical environment in the grafting zone [1-6].

Complications occur in up to 37-80% of free vascularized fibular graft (FVFG) reconstructions [7]. Friedrich et al. reported that, of 33 patients, 17% experienced complications, while 7 patients experienced failure of the allograft reconstruction [8]. Hornicek et al. reported that nonunions occurred in 27% of 945 patients [9]. Therefore, the repair of large defects (> 6 cm long) associated with bone tumors can be challenging for orthopedic surgeons.

Recently, studies have demonstrated that the combination of FVFG and a locking plate is a viable option for the management of large skeletal defects from open fracture and infection [6]. The mechanical environment related to the bone graft, such as the length, and fixation

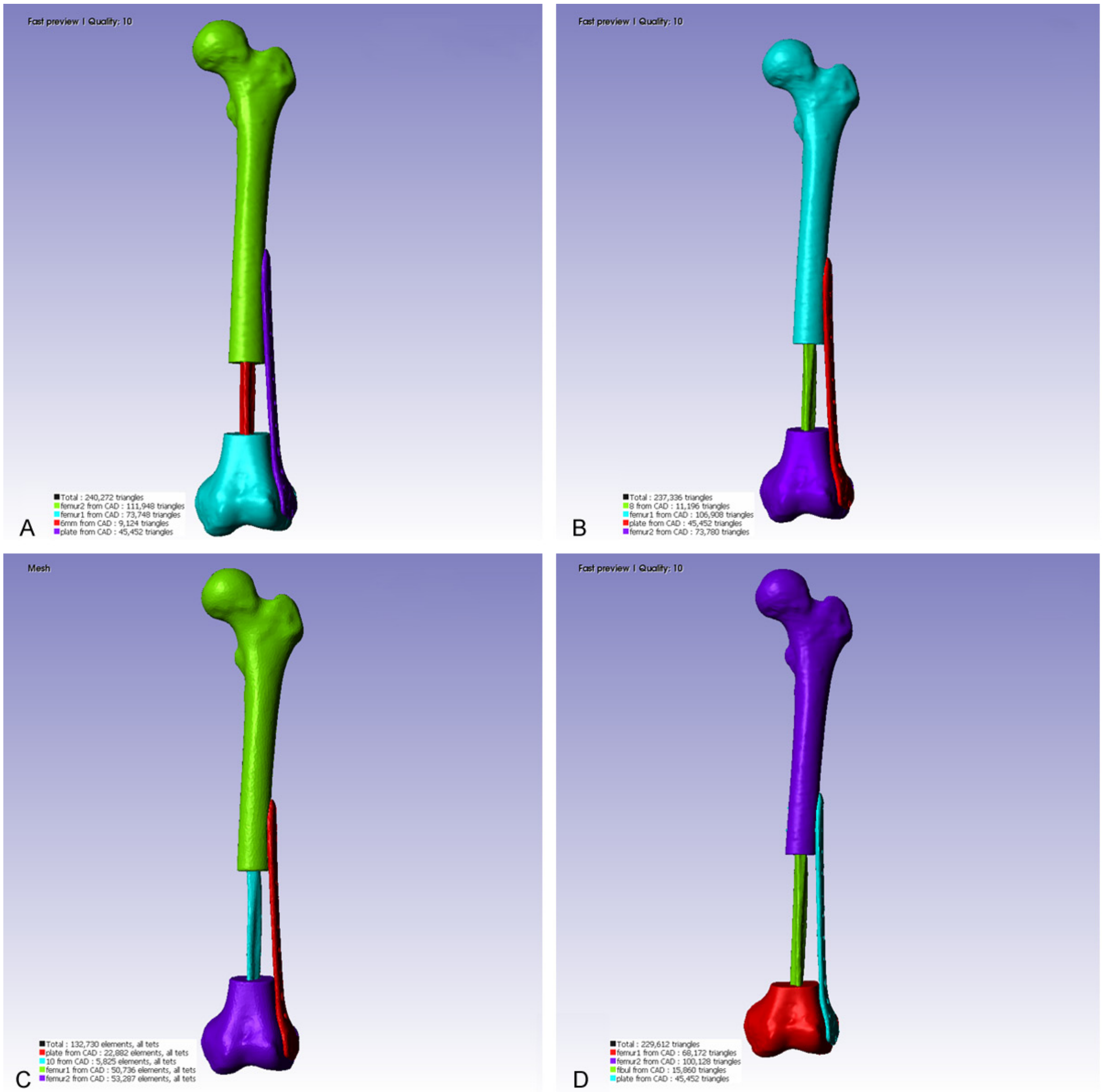

Figure 1. CAD models of dismal femur bone tumor resections with reconstruction locking plates and fibular (A) 6 cm, (B) 8 cm, (C) 10 cm, (D) 12 cm.

mode during reconstruction are important factors for successful fixation.

To the best of our knowledge, there have been no studies to investigate the effect of the fibular graft length on the biomechanics after fixation using a fibular graft with a locking plate to reconstruct a distal femoral tumor defect. The purpose of the present study was to test the effects of fibular graft length in addition to the displacement and stress distribution of the fibular graft locking plate using three-dimensional finite element analysis (FEA). We hypothesized that a long bone graft may result in greater stress that would eventually increase the risk of loosening.

Patients and methods

This study is approved by The Research Ethics Committee of Liu Hua Qiao Hospital. It is in accordance with National Statement on Ethical Conduct in Research Involving Humans. This study involves in the use of human femur obtained from male volunteer when performed CT scan, we will be strict inspection in accordance with relevant regulations of medical ethics. We carried out this research work under

Table 1. Material property of different parts of the model [10-13]

Material	Young's Modulus (MPa)	Poisson's ratio
Cortical bone	16800	0.3
Trabecular bone	840	0.2
Fibula	15000	0.3
Ti-6Al-4V	1.06 × 105	0.33

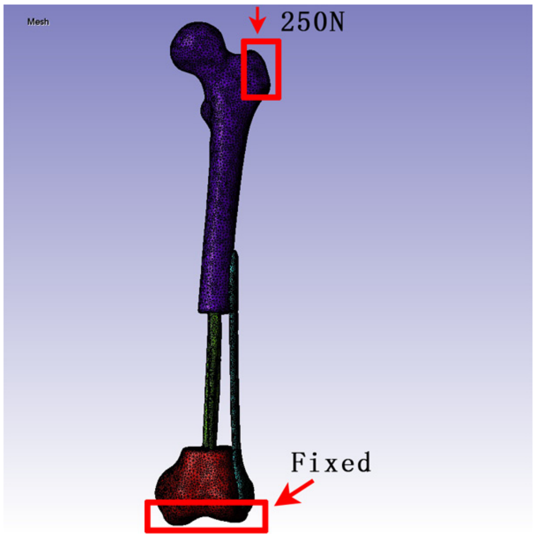

Figure 2. Boundary and loading conditions of the femoral models.

the supervision of The Ethics Committee. This research correspond to Ethics Committees and safeguard patient interests. In brief, we believe this study has no major ethical concerns, and the risk is reduced minimally. We obtained the written consents from the participants before the study. To construct the model, the left leg of a 25-year-old male volunteer (body weight, 65 kg; height, 170 cm) was scanned using dual-source, 64-slice spiral computed tomography (SOMATOM Definition CT, Siemens Healthcare, Forchheim, Germany) with a slice thickness of 0.7 mm and an image matrix size of 512 × 512. The images were processed as data files in the Digital Imaging and Communications in Medicine (DICOM) format using an online work-station. The femur, fibula, and locking plate models were constructed using the ScanIP Module of the Simple ware 5.0 software (Department of Orthopedics, Guangzhou General Hospital of Guangzhou Military Command, Guangzhou, China), and the models were exported in the "STL" format. The length of the femoral defect was modeled at 2 cm increments between 6 cm and 12 cm: 6 cm, 8 cm, 10 cm, and 12 cm. The defect was filled, and double barrel FVFG models were constructed according to the conventional reconstruction technique. A 16-hole locking plate was fixed to the distal femur with 3 proximal and 4 distal cortical screws according to the manufacturer's instructions (**Figure 1**).

Mesh

The femur and fibula are composed of cortical and cancellous bone; the material properties were derived from previously reported data by Shilei et al. The locking plate was assumed to be made of Ti-6Al-4V alloy, the elastic module was set at 1.06 × 105 MP, and the Poisson ratio was 0.33 (**Table 1**). The materials were assumed to be homogeneous, continuous, and isotropic elastic materials and 3-D 4-Node Tetrahedral Structural Solid elements were selected to plot three-dimensional models.

Boundary conditions and loading

The compression simulated a one-leg standing condition for a subject weighing approximately 65 kg, and 33% of the 250-N compression body joint force were applied on the models when standing (**Figure 2**) [10]. The displacements of the surface-bound nodes in the distal femur along the X, Y, and Z axes were set at zero. The XY and XZ plane rotation angles were also set at zero, whereas the YZ plane was allowed to rotate freely. The model was performed using ABAQUS software (ABAQUS v.6.9, Dassault Systems, MA, USA).

Statistical analysis

All Von Mises stresses are presented as mean ± S.E.M, and analyses were conducted using SPSS 13.0 (SPSS, Southern Medical University, Guangzhou, China), Comparisons between the lengths were conducted using a one-way ANOVA followed by post-hoc LSD multiple comparison tests. $P < 0.05$ was considered statistically significant.

Results

The mean Von Mises stress distributions for CAD models are shown in **Figure 3**.

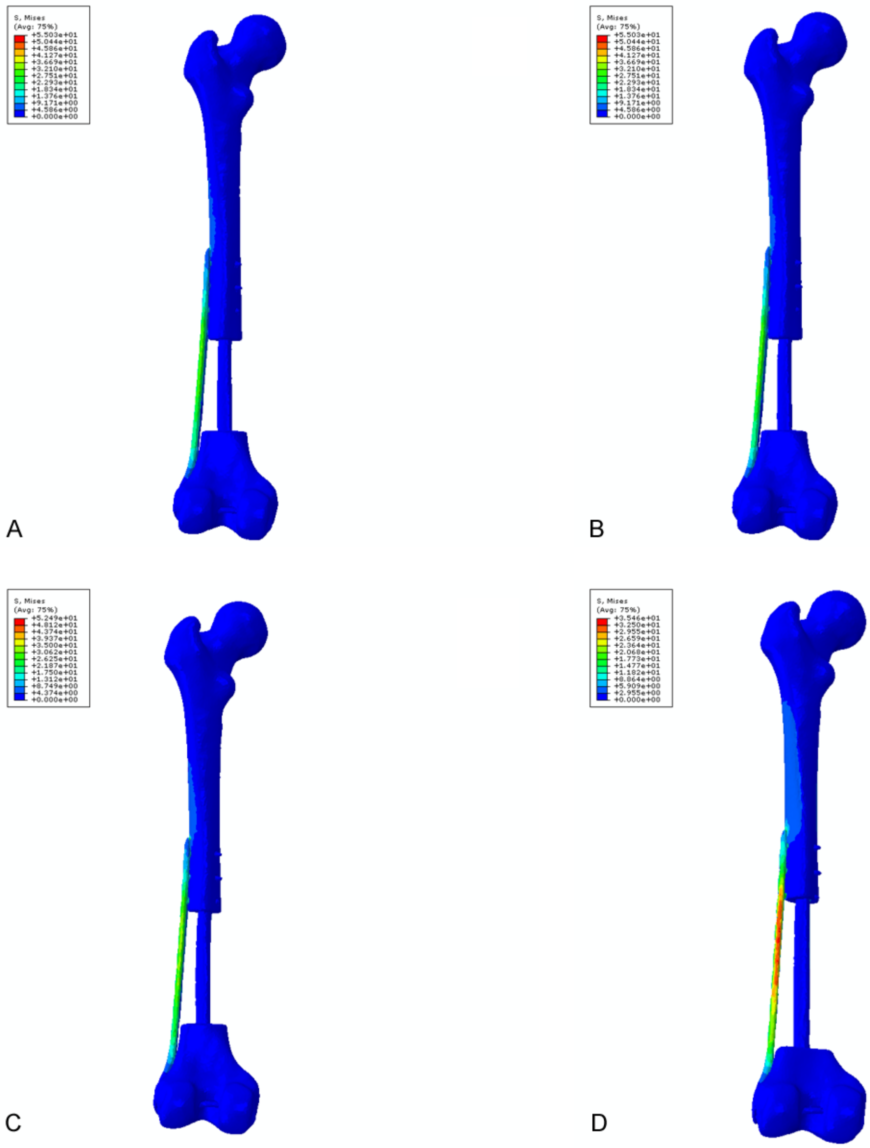

Figure 3. Von MisesStress distribution within the area between the fibular grafting and the locking plate in different CAD modes. A. 6 cm, B. 8 cm, C. 10 cm, D. 12 cm.

The mean Von Mises stress distributions for the bone grafts were as follows: 6 cm, 6.26 Mpa (SD 0.13); 8 cm, 6.26 Mpa (SD 0.15); 10 cm, 6.19 Mpa (SD 0.09); and 12 cm, 6.55 Mpa (SD 0.15) (**Figure 4**). The results of the 6 cm, 8 cm, and 10 cm bone grafts were similar ($P > 0.05$), while the Von Mises stress distribution was significantly higher with the 12-cm bone graft than with any of the other 3 lengths ($P < 0.05$) (**Figure 5**).

The mean locking plate Von Mises stress distributions were as follows: 6 cm bone defect model, 28.02 Mpa (SD 0.20); 8 cm bone defect model, 28.55 Mpa (SD 0.83); 10 cm bone defect model, 28.26 Mpa (SD 0.33); and 12 cm bone defect model, 32.01 Mpa (SD 1.97) (**Figure 6**). The results of the 6 cm, 8 cm, and 10 cm bone defect models were similar ($P > 0.05$), while the Von Mises stress distribution was significantly higher with the 12 cm bone defect model than with any of the other 3 lengths ($P < 0.05$). In addition, too much stress was present on the exterior of the locking plate with the 12 cm bone defect model (**Figure 7**).

The maximum displacement of the bone graft was 0.079 mm, 0.13 mm, 0.18 mm, and 0.2

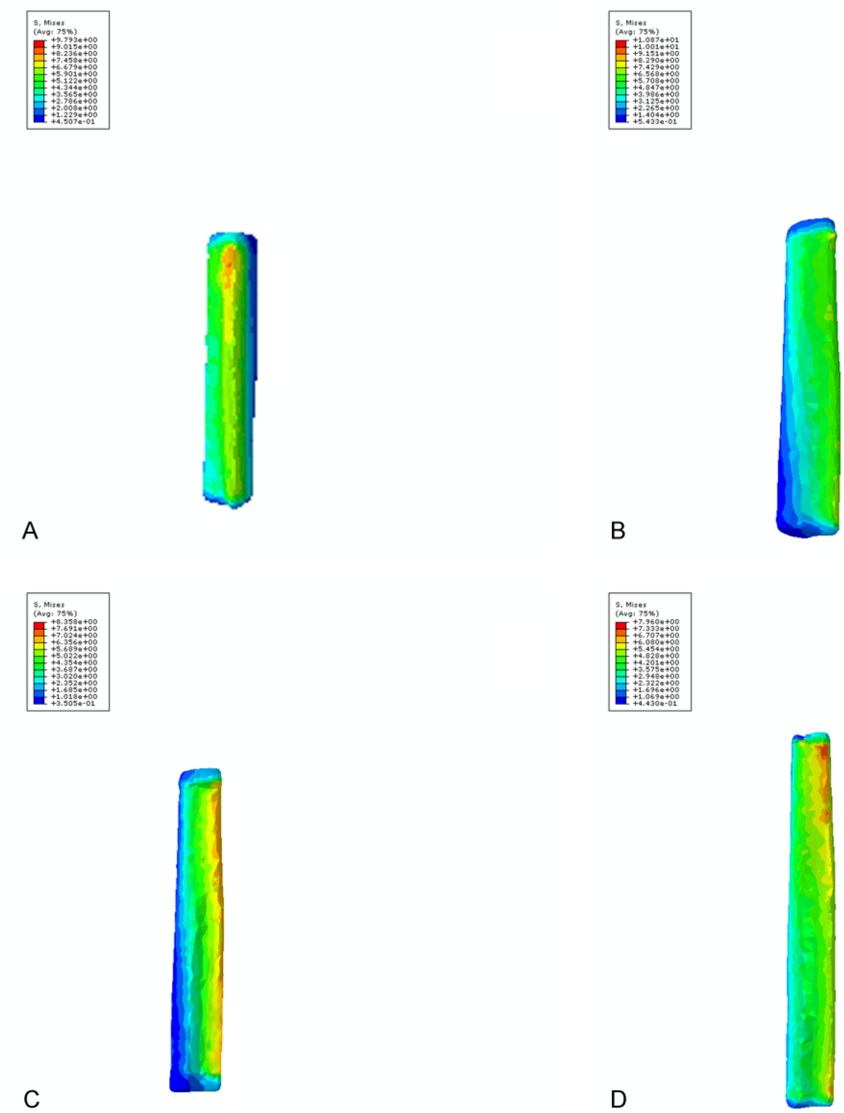

Figure 4. Von Mises stresses in the fibular grafting zone in different grafting modes. A. 6 cm, B. 8 cm, C. 10 cm, D. 12 cm.

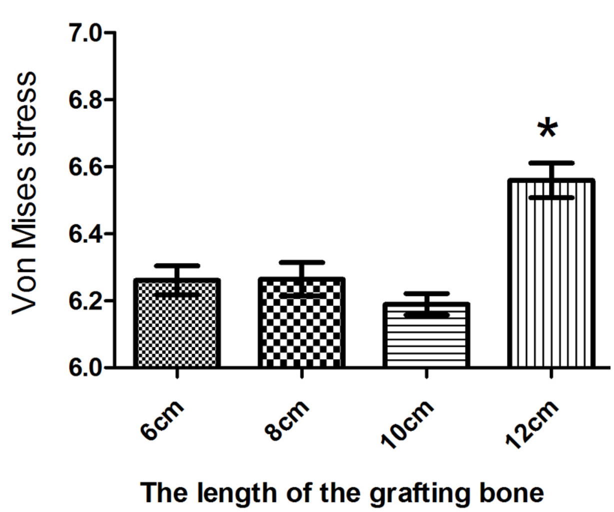

Figure 5. Comparison of Von Mises stresses fibular grafting in different CAD modes, demonstrating has significantly differences in distribution 12-cm bone graft than with any of the other 3 lengths.

mm, respectively (**Figure 8**), while the locking plate displacement was 0.29 mm, 0.33 mm, 0.34 mm, 0.36 mm (**Figure 9**).

Discussion

In the present study, the use of a bone graft that was 12 cm long, combined with a locking plate, resulted in significantly greater Von Mises stress than the other 3

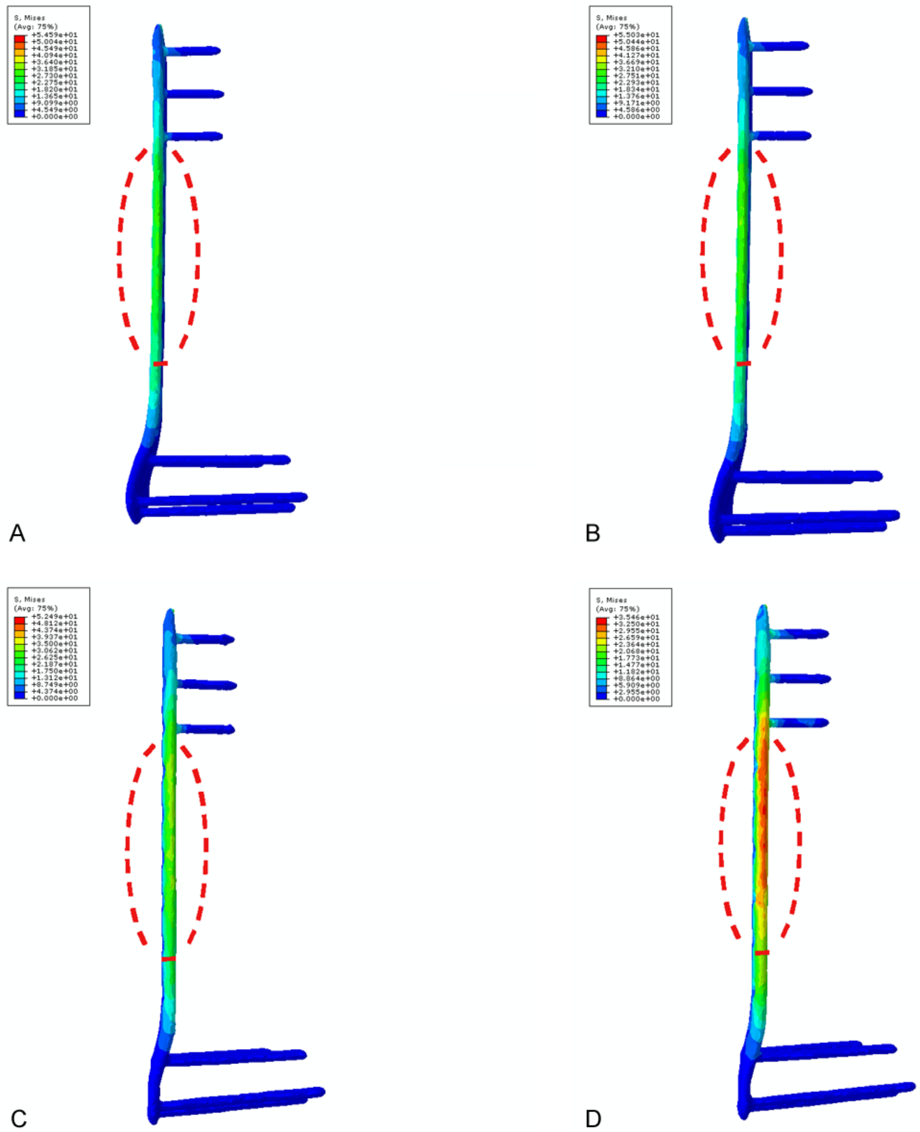

Figure 6. Von Mises stresses in the locking plates zone in different CAD modes. A. 6 cm, B. 8 cm, C. 10 cm, D. 12 cm.

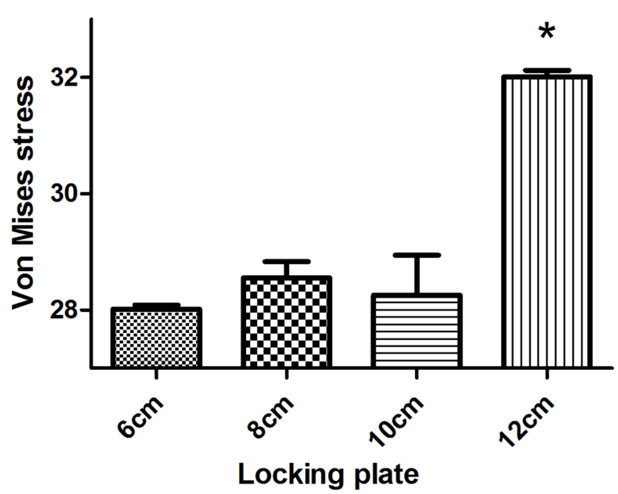

Figure 7. Comparison of Von Mises stresses locking plate in different CAD modes, demonstrating has significantly differences in distribution 12 cm bone graft than with any of the other 3 lengths.

lengths, which resulted in similar stresses. The greater Von Mises stress could result in fracture of the locking plate and require a revision of the procedure. In addition, a high level of stress was also present on the exterior of the 12 cm bone graft, which could result in nonunion between the bones. Furthermore, the displacement of the fibular bone increased with increasing bone graft length. These results collective-

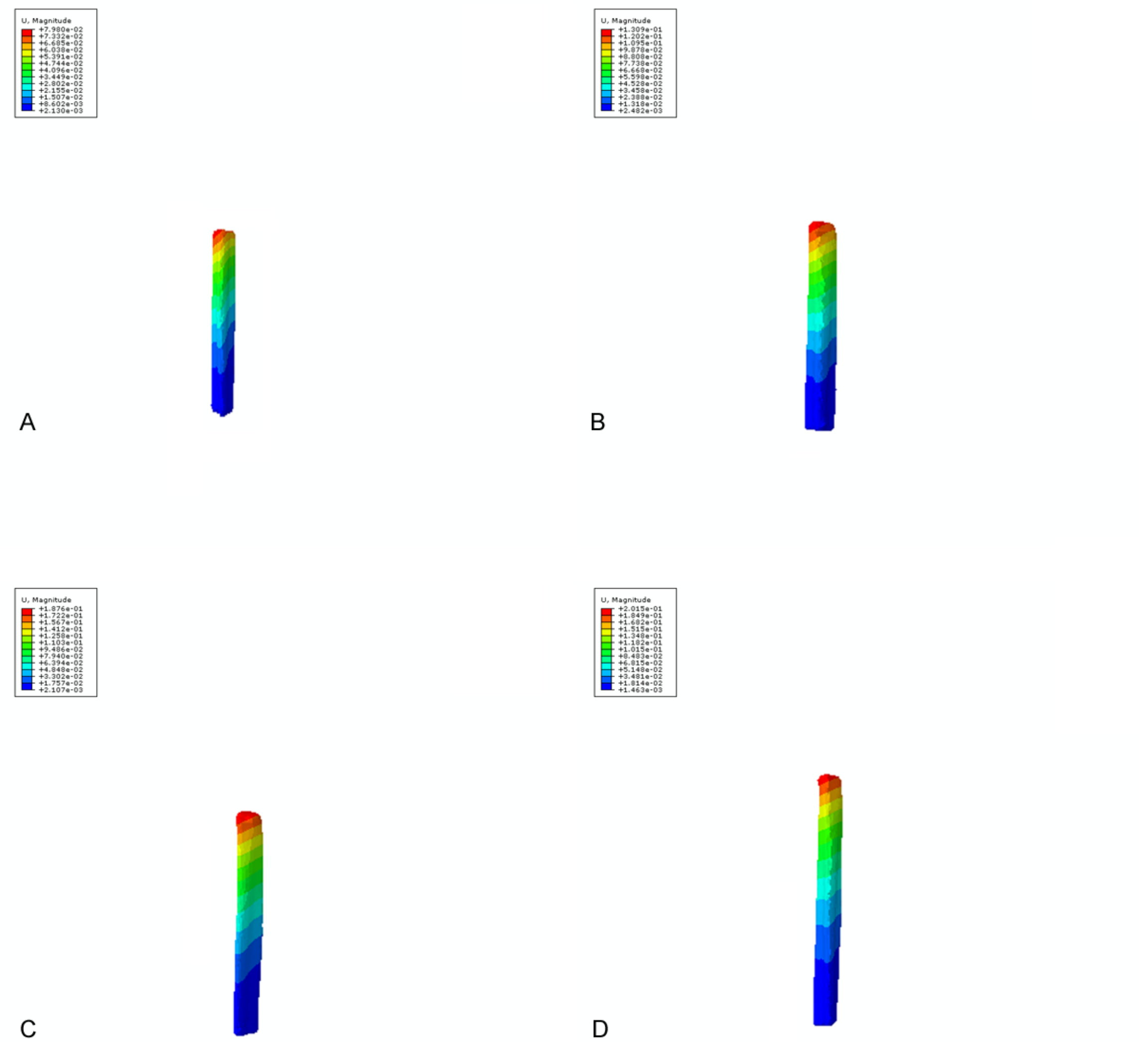

Figure 8. Fibular graft displacements. Model (A) 6 cm, (B) 8 cm, (C) 10 cm, (D) 12 cm.

ly indicate that, to reduce complications, the bone graft in FVFG should not exceed 12 cm when combined with a locking plate for distal femoral tumor defect treatment.

The distal femur and proximal tibia are more prone to malignant bone tumors than other sites. In these large bones, tumor defects are often treated with FVFG combined with a locking plate, because FVFG is known to accelerate the bone healing process and is biomechanically stronger than a conventional fibular graft. FVFG provides an important source of vascularity to scarred vascular recipient sites [14].

Previous studies have shown the efficacy of locking plates in clinical applications, reporting relatively low rates of complications in the treatment of nonunion fractures. For example, Chen et al. compared retrograde intramedullary nailing and locking plate fixation for a distal femur fracture; the locking plate with the allograft construction significantly stabilized the fracture gap and reduced the implant stress [15]. The design differences of the locking plate, compared to conventional plates, include a stable angular interface between the screws and plate, without bone contact. This preserves the periosteal bone perfusion and blood supply, promoting bone union, minimizing stress shielding, and creating an excellent biological and mechanical environment [16]. The results of the present study support the use of the locking plate system as an optimal internal biomechanical connection; all of the bone graft lengths were below the threshold for displace-

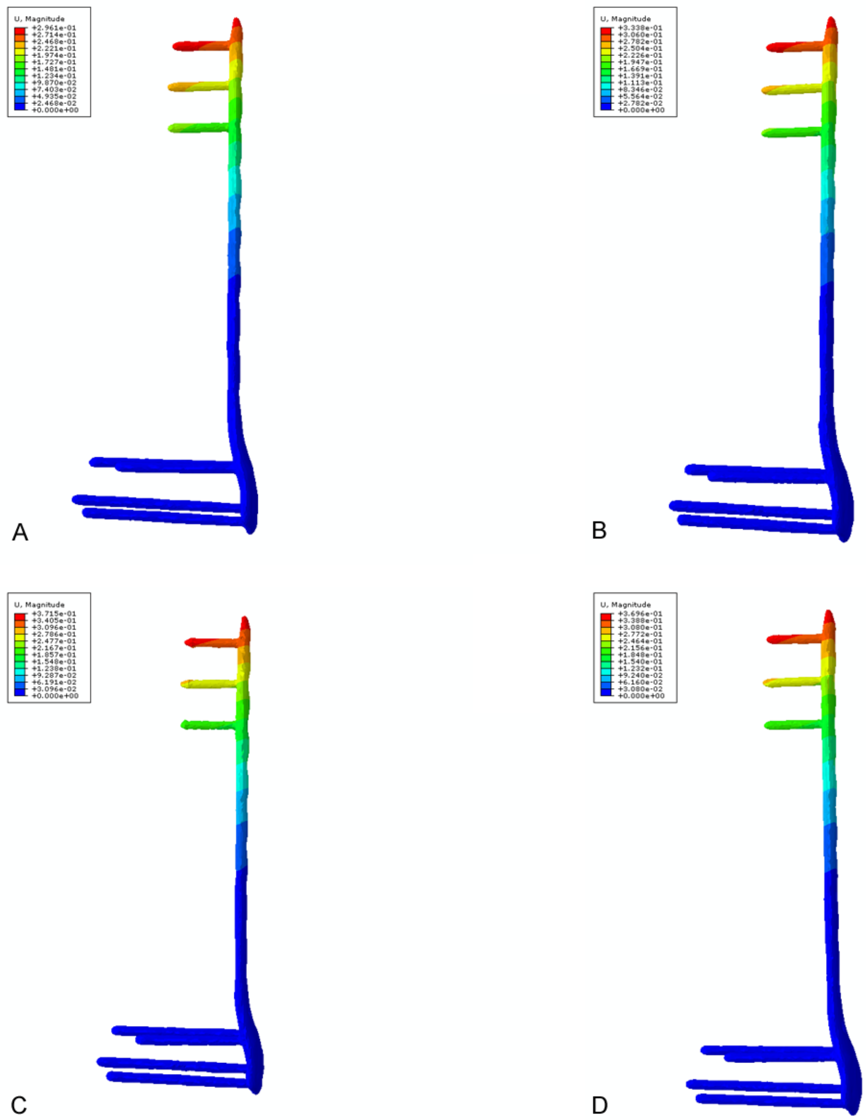

Figure 9. Locking plates displacements. Model (A) 6 cm, (B) 8 cm, (C) 10 cm, (D) 12 cm.

ment. Lienau et al. reported that < 0.5 mm displacement can promote fracture union and > 1 mm displacement can delay the union [17]. Therefore, the locking plate may have contributed to the bone union in the present study.

Comparisons of other treatments for femoral defects have been conducted. Wähnert et al. tested angulated screws in locked plate constructs and reported that they do not provide better stability than parallel screws [18]. Wieding et al. investigated titanium scaffolds for large segmental bone defects, and the results showed defect gap alterations between 0.03 mm and 0.22 mm for the applied scaffolds and 0.09 mm for the intact bone. These results indicated that minimizing the amount of inner core material does not have a large influence [19].

This study has certain limitations. First, the soft tissue was not included in the model, which did not allow for evaluation of the effect of muscle force on the mechanical condition. Second, the materials and tissues were assumed to be homogeneous, continuous, and isotropic elastic materials, which do not necessarily reflect their true composition, although similar assumptions have been made previously [20]. Finally, in three-dimensional models, FEA only provides an approximate prediction of the biomechanics that can predict likely areas of fracture failure and screw loosening. In this situation, the locking plate will break if the applied static stress is greater than the strength of the material. However, even when the biomechanics are designed adequately, the more complex biological effects of walking, stair climbing, stumbling, or temperature changes on the femur are not known and require further study.

Conclusion

Significantly greater Von Mises stress was observed at the 12 cm bone graft and locking plate than with the shorter bone grafts. Therefore, we recommend that, to avoid complications, the bone graft should not exceed 12 cm when using FVFG in combination with a locking plate to treat a distal femoral tumor defect.

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