

Is Double-Strut Fibula Ankle Arthrodesis a Reliable Reconstruction for Bone Defect after Distal Tibia Tumor Resection? -A Finite Element Study Based on Promising Clinical Outcomes

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Abstract

Background: There are different surgical methods for primary malignant tumor located at distal tibia. Previous studies have reported that double-strut fibula ankle arthrodesis is an alternative reconstruction. The purpose of this study was to investigate the biomechanical effect of double-strut fibula ankle arthrodesis by finite element analysis (FEA).

Methods: Computer aided design software was used to established three-dimension models. Three different models were construct: normal tibia-fibula-talus complex (Model A), double-strut fibula ankle arthrodesis (Model B), and reconstruction by ipsilateral fibula (Model C). We used FEA to evaluate and compared the biomechanical characteristics of these constructs. Simulated loads of 600 N was applied to the tibial plateau to simulate balanced single-foot standing. Output results representing the model von Mises stress, and displacement of the components were analyzed.

Results: Construct stiffness was significantly increased when the internal plate fixation was used. For axial loads, Model B (963.79 N/mm) was significantly stiffer than the construct of Model A (430.76 N/mm), and Model C (616.06 N/mm), indication Model B was more stable. Maximum stress on the fibular graft occurred on the proximal end. There were no significant differences in von Mises stress and stress distribution of fibular graft in Model B (22.73 MPa) and Model C (23.69 MPa). In Model B, the ipsilateral fibula in Model B has a higher value of stress (12.07 MPa) than that in Model A (0.67 MPa), indicating the ipsilateral fibula shared load after fusion with talus. For axial load, displacement at the fibular graft in Model B (0.37 mm) was significantly less than that in Model C (0.82 mm).

Conclusions: Our computational findings suggest that double-strut fibula ankle arthrodesis is an acceptable construct for distal tibia defect and the ipsilateral fibula shared load after fusion with talus.

Introduction

Primitive malignant neoplasm occurs at distal tibia is rare and typically have a better prognosis than other sites [1]. But it is precisely because of the rare nature that no consensus has been reached concerning the gold standard treatment. Limb-sparing method is tumor resection and reconstruction by using prosthesis, allograft, autograft recycled tumor-bearing bone, or bone transport as well as ankle arthrodesis [2–9]. Each technique has pros and cons, and the best treatment modality is yet clear. In a large series study, Zhao et al.[10] found similar limb function evaluated by Musculoskeletal Tumor Society (MSTS) scores between autograft reconstruction (81%) and amputation (82%), which were both superior to allograft reconstruction (67%). Meanwhile, they have introduced a double-strut fibula ankle arthrodesis technique to restore limb continuity. A mid-term (53 ± 46 months) study conducted by the same team [11] in 2019 proved that double-strut fibula ankle arthrodesis is capable of achieving durable ankle fusion and limb function (MSTS 83%) with low rate (11%) of complications.

Although promising clinical outcomes has been reported, whether double-strut fibula ankle arthrodesis is stable, and beneficial for patients still lack high-quality clinical follow-up and mechanical evidence. The

purpose of this study was to investigate the biomechanical effect of double-strut fibula ankle arthrodesis by finite element analysis (FEA). Moreover, we compared this construct with normal bone model and the reconstruction by ipsilateral fibula and ankle arthrodesis. These biomechanical data may provide a theoretical reference for clinical treatment of bone defect of distal tibia.

Materials And Methods

Our department started to use this double-strut fibula ankle arthrodesis for malignant tumors of distal tibia in 2007 (Fig. 1). Surgical technique was introduced in previous study[11]. Up to 2020, a total of 9 patients with distal tibia tumors received this method. The resection length of distal tibia ranged from 7 to 20 cm, averaged 13 cm. Retrospectively, the mean follow-up duration was 53 months (Standard deviation (SD), 46 months). The average bone union time of the proximal junction and distal junction was 10.5 months and 8.7 months, respectively. Limb function after surgery was 83% assessed by MSTs score system. There was no deep infection, plate breakage, or bone graft fracture during the followup time.

Three-dimensional reconstruction models

A healthy adult male volunteer (age, 24 years; height, 168 cm; weight, 60 kg) was selected, and his right lower limb was placed in a neutral position to undergo computerized tomography (CT). The DICOM Digital Imaging and Communications in Medicine (DICOM) data were imported into Mimics 21 (Materialise Corp., Belgium). Definition of cortical bone, cancellous bone, and marrow cavity were established based on CT images with different gray values. Then three-dimension (3D) CT model data were obtained. This study simulated a distal tibial osteotomy of 13 cm according to clinical data. Then structure of each bone in IGS format was transferred to Geomagic software 2017 (Raindrop Company, USA). Processing in Geomagic software was done to obtain the volumes of the bones. Stp files of bone's volume were imported into Solidworks software 2017 (Dassault Systemes Corp., French). Finally, the solid objects representing the bones were assembled within Solidworks to make 3D tibia-fibula-talus complex. The appropriate computed model of plate and screw was supplied by Zimmer Inc. (USA). Finally, three different models were assembled using Solidworks: normal tibia-fibula-talus complex (Model A), double-strut fibula ankle arthrodesis (Model B), and reconstruction by ipsilateral fibula (Model C) (Fig. 2).

3D models of reconstructions in SLDPRT files were then input into FEA software Ansys 17.0 (Ansys Corp., USA). In Ansys, tetrahedron meshes of the models were created (Fig. 3). Interaction between the screw/bone interfaces and autograft/bone were defined as tie. The screws were fixed into the plates and tibia cortices and talus. All bone were assumed to behave as homogeneous, isotropic and linearly elastic material. The cortical and cancellous portions of the distal tibia were modeled with Young's modulus of 14000 MPa and 700 MPa and Poisson ratio of 0.3 and 0.2, respectively[12–14]. Plate and screws were assigned an elastic modulus and Poisson's ratio of 110,000 MPa and 0.3 respectively[15, 16]. The material properties of bone and implant components are shown in Table 1.

Table 1
Material properties used in finite element models

Material	Young's modulus (E)	Poisson ratio (ν)
Plate, screw	110000	0.3
Cortical bone	14000	0.3
Cancellous bone	700	0.2
Fibula, talus, calcaneus	7300	0.3
cartilage	3	0.4

Boundary conditions and validation of model

The talus was fixed in all degrees of freedom. A vertical compressive force of 600 N corresponding the body weight of a person weighing 60 kg was applied to the tibial plateau in full extension to simulate balanced single-foot standing to bear the entire body's weight.

Integral stability of the constructs was evaluated to compare construct stiffness. Regional stability of the constructs was assessed by exploring displacement at the fibula, fibular graft after fixation under axial loads. The von Mises stress (VMS) values and stress distribution on all components of the models were determined.

Results

The total number of nodes were 89309, 775254, and 671852 in Model A, B, and C, respectively, and total amount of elements were 52898, 457092, and 395191 in Model A, B, and C respectively.

Construct stiffness

The maximum von Mises stress and stress distribution on three constructs are shown in Fig. 4. For axial load, Model B (963.79 N/mm) was significantly stiffer than the construct of Model A (430.76 N/mm), and Model C (616.06 N/mm). Overall, construct stiffness was significantly increased when the internal plate fixation was used. However, the axial stiffness of double-strut fibular construct was approximately 1.6 times larger than that of the ipsilateral fibular reconstruction.

Implant stress

For axial load, maximum stress on the implant occurred on the distal locking screw, and proximal locking screw, respectively. For Model B, the ipsilateral fibular shared the load and decreased the risk of implant failure or graft fracture. The maximum von Mises stress of implant after double-strut fibular construction (203.14 MPa) was decreased by 13.8% compared to that in Model C (235.6 MPa) (Fig. 5).

Graft stress and displacements

For axial direction, maximum stress on the fibular graft occurred on the proximal end. There were no significant differences in von Mises stress and stress distribution of fibular graft in Model B (22.73 MPa) and Model C (23.69 MPa) (Table 2). In Model B, the ipsilateral fibula was reserved and fused with talus by a screw. Noteworthy, the result revealed that ipsilateral fibula in Model B has a higher value of stress (12.07 MPa) than that in Model A (0.67 MPa), indicating the ipsilateral fibula shared load after fusion with talus (Fig. 6).

Table 2
Maximum stress (MPa) of the three models when loading 600N

Component	Model A	Model B	Model C
Ipsilateral Fibula	0.67 MPa	12.07 MPa	/
Fibular graft	/	22.73 MPa	23.69 MPa
Implant	/	203.14 MPa	235.6 MPa

For axial load, displacement at the fibular graft in Model B (0.37 mm) was obviously less than that in Model C (0.82 mm), indicating the graft in Model C has a higher risk of graft fracture (Fig. 7). Table 3 shows the displacement values of four models in three axes.

Table 3
Displacement values (mm) in X, Y and Z axes

Load	Model	Axes		
		X-axis	Y-axis	Z-axis
600N	Model A	4.00mm	0.84mm	1.39mm
	Model B	0.57mm	3.04mm	0.62mm
	Model C	2.13mm	2.81mm	0.97mm

Discussion

According to the literature, ankle fusions and reconstruction with bone graft is the primary methods for salvaging the distal tibia[9]. The fibular graft is the widely used bone graft that is easy to obtain and results in minimal donor-site morbidity[17]. It can be inserted into the medullary canal of the tibia perfectly. Then, fibular graft has the bability to become hypertrophy under the stimulation of weight-bearing after bony union[18, 19]. When this bone construction is created, initial stability is a guarantee of host-graft healing. However, it is difficult to investigate the biomechanical effect in vivo. Beside, it is tough to enroll enough cases to detect the clinical outcomes of different surgical methods due to the rare incidence of this disease. As FEA has been widely used for mechanical analyses, it has the potential to

predict the preoperative mechanical environment, help the surgeon to decide the optimal reconstruction. Therefore, we aim to evaluate the initial stability of double-strut fibula ankle arthrodesis.

This work has several limitations. Firstly, the FEA model was based on the anatomy of a single patient. Secondly, the role of muscles or ligaments was not simulated because of the difficulty in assessing the soft tissue changes after excision and reconstruction of the distal tibia. Therefore, the stability offered by the surrounding soft tissues was ignored. But, this technical limitation affected all the groups equally and it didn't question the validity of our findings. Thirdly, it is a static simulated study and further studies are needed to explore the dynamic loading process. Finally, anatomical variations in the distal tibia and the extent of excision may affect the results.

According to the vertical pressure analysis, cracks usually occurred at the area of the concentrated stress and with obvious displacement. In our study, the maximum stress of fibular graft in Model B and Model C were similar (22.73 MPa vs. 23.69 MPa) when loading the vertical force of 600 N, which were both acceptable. In Model B and Model C, we noted that concentration of stress was at the implant. This can be easily explained by the fact that the plate can resist the upward displacement effectively and protect the fibular graft in early time. The outcome exhibited that fibula in Model B has a higher value of stress (12.07 MPa) than that in normal bone model (0.67 MPa), indicating the ipsilateral fibula acts as an ancillary structure for weight-bearing. It upholds the current recommendations that the double-strut reconstruction can provide satisfactory initial stability [10, 11].

The Model C simulated the reconstruction method of ankle fusion with centralisation of the fibula which was reported by Kundu et al. [7]. In these authors' study, 9 patients with distal tibia tumor underwent this surgical option, resulting in a mean MSTS score of 76%. There was no stress fracture of the fibula after surgery, however, an angulation at the proximal fibula graft was observed in one case. In this study, we found that this technique of centralization of fibular graft was not stable enough compared with double-strut fibula reconstruction, and has a high rate of fracture of fibular graft in early period after surgery. Therefore, Kundu et al. [7] recommended that weight-bearing was not allowed in the first 8 weeks. Guarded weight-bearing was carried out 8–10 weeks onward when radiological bone union began, and the full-leg cast was replaced by a below-leg cast after 16–20 weeks, when radiographs showed sign of bone union. Therefore, this procedure requires quite a long time to get rid of cast and to start full weight-bearing.

Prosthesis can provide initial stability, resulting in good early function, however, it is still associated with a significant set of complications such as high risk of infection, loosening, talus collapse, and ankle instability [9]. Due to lack of muscle coverage in this distal tibia, it will complicate the reconstruction of prosthetic replacement, and burdened the prosthesis with long-term complications. A mid-term study and a long-term study exhibited that the aseptic loosening and infection were main reasons of prosthetic reconstruction failure [20, 21]. Zhao et al. [28] performed a literature review comparing prosthetic replacement with biological reconstruction (allograft or autograft), and revealed that autograft or allograft reconstruction performed better than prostheses. Therefore, in this study, we did not investigate

the biomechanical effect of prosthetic replacement. However, in recent years, the introduction of 3D printed prosthesis with surface of bone-growth may reduce the complications, further long-term study is needed.

The non-vascular autogenous fibular graft has some important advantages over other donor sites due to its length, geometry and mechanical strength. The fibula being a long, straight tubular bone, with perfect shape allows tibial intramedullary insertion. And it is an easy, inexpensive biological procedure that does not require micro-vascular skills. The current FEA study suggest that reconstruction with fibular graft after tumor resection of distal tibia is an accept solution, but the additional plating is required to sustain initial stability.

Conclusion

The computational findings suggest that double-strut fibula ankle arthrodesis is an acceptable construct for distal tibia defect and the ipsilateral fibula shared load after fusion with talus.

Abbreviations

FEA: finite element analysis; MSTs: Musculoskeletal Tumor Society; SD: Standard deviation; CT: Computerized tomography; DICOM: Digital Imaging and Communications in Medicine; 3D: Three-dimension; VMS: Von Mises stress

Declarations

Ethics approval and consent to participate

The implementation of this study was approved by the institutional ethics committee of the Peking University People's Hospital (2017PHB181-01). Informed consents from the volunteer was obtained.

Consent for publication

Informed written consent were obtained from the volunteer to publish their personal details information.

Availability of data and materials

The datasets used in the study are available from the corresponding author on reasonable request.

Competing interests

Each author certifies that neither he, nor any member of his immediate family, has funding or commercial associations that might pose a conflict of interest in connection with the submitted article.

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Authors' contributions

ZQZ: Collecting the data, Analyzing the data, Preparing the manuscript.

TQY: Designing the study, Analyzing the data, Preparing the manuscript, Supervision.

XDT: Collecting the data, Preparing the manuscript.

WG: Collecting the data, Preparing the manuscript.

RLY: Collecting the data, Preparing the manuscript.

All authors read and approved the final manuscript.

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Figures



Figure 1

(A) Preoperative X-ray film showing osteosarcoma of distal tibia. (B) Intraoperative photo showing that a non-vascularized fibula transfer harvested from unaffected limb restore the tibial continuity, which parallels to the ipsilateral fibula. Fixation was carried out by plate and screws. The talus and ipsilateral fibula were fused. (C) Postoperative X ray film.

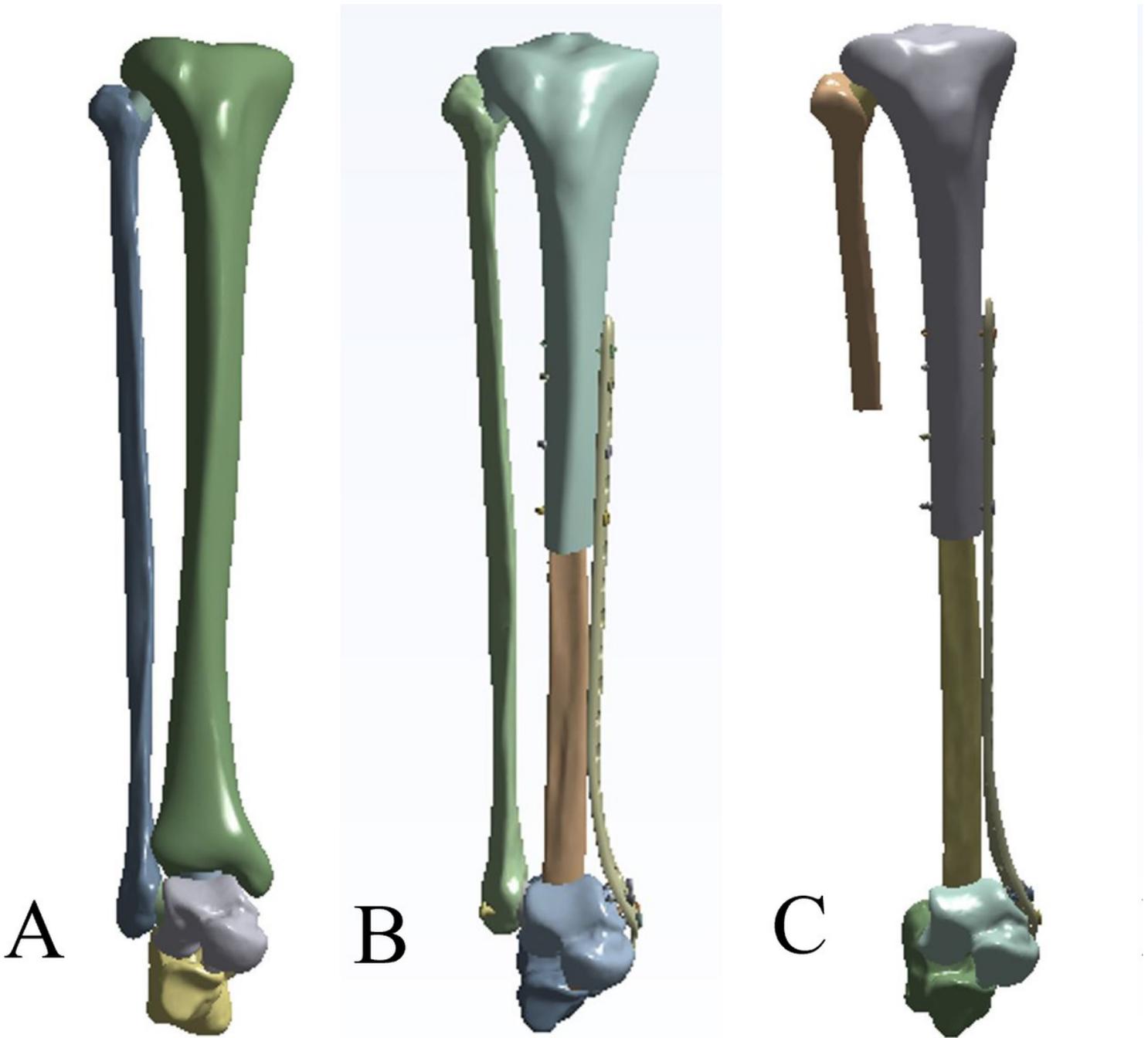


Figure 2

3D models for simulation calculation. (A) normal tibia-fibula-talus complex, (B) double-strut fibula ankle arthrodesis, and (C) reconstruction by ipsilateral fibula—centralisation of the ipsilateral fibula.



Figure 3

Tetrahedron volume mesh models.

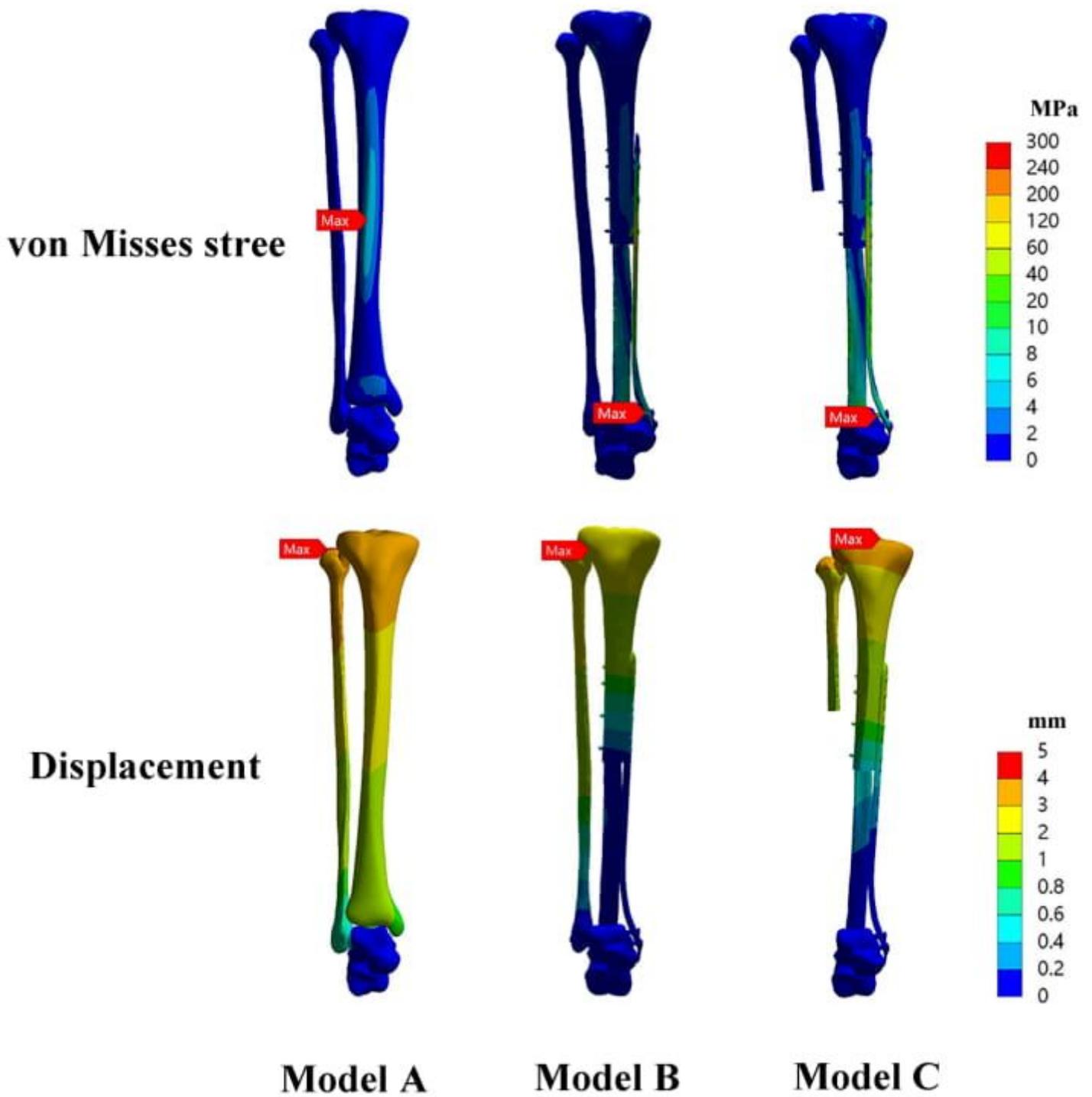


Figure 4

The pictures indicate VMS and displacement distributions in the three models when a vertical compressive force of 600 N corresponding the body weight of a person weighing 60 kg was applied to the tibial plateau.

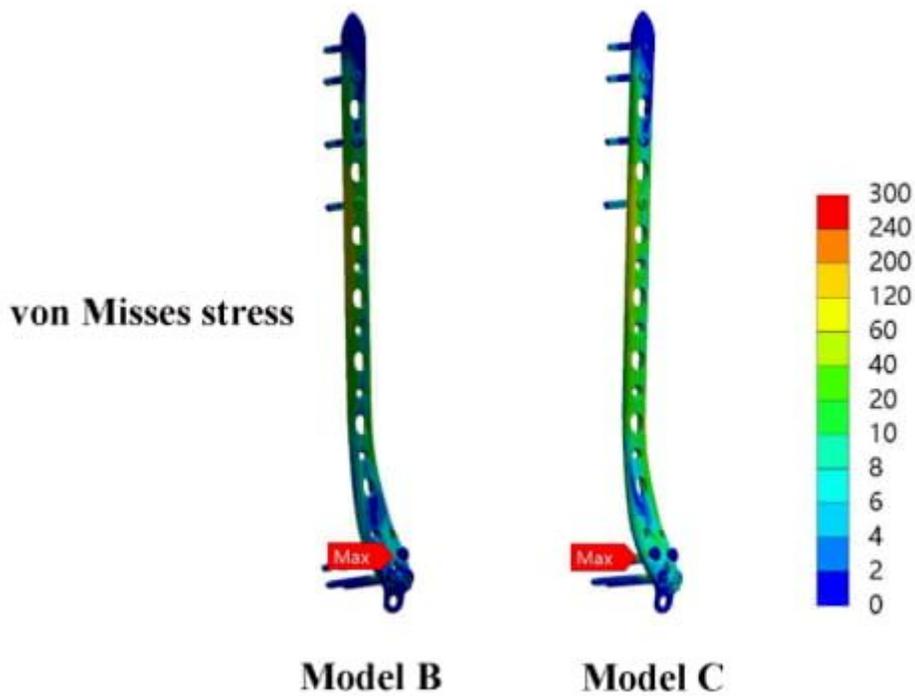


Figure 5

The maximum VMS of implant in Model B was 203.14 MPa, was decreased by 13.8% compared to that in Model C (235.6 MPa).

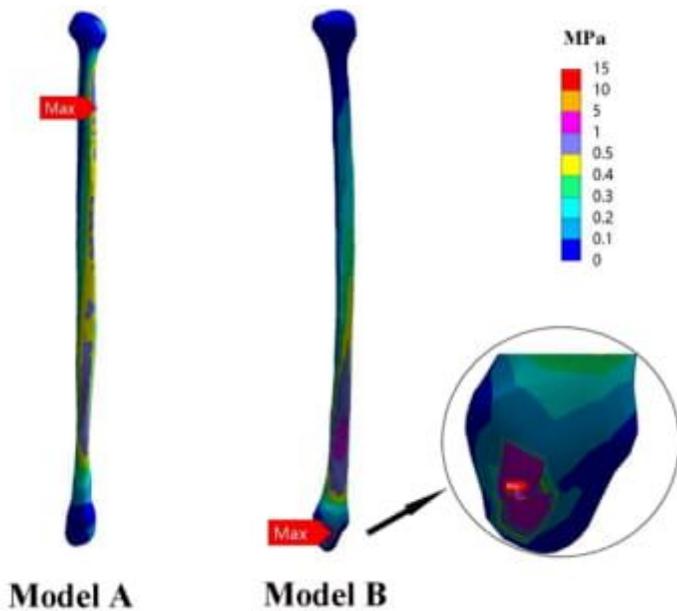


Figure 6

The ipsilateral fibula in Model B has a higher value of stress (12.07MPa) than that in Model A (0.67MPa), indicating the ipsilateral fibula shared load after fusion with talus.

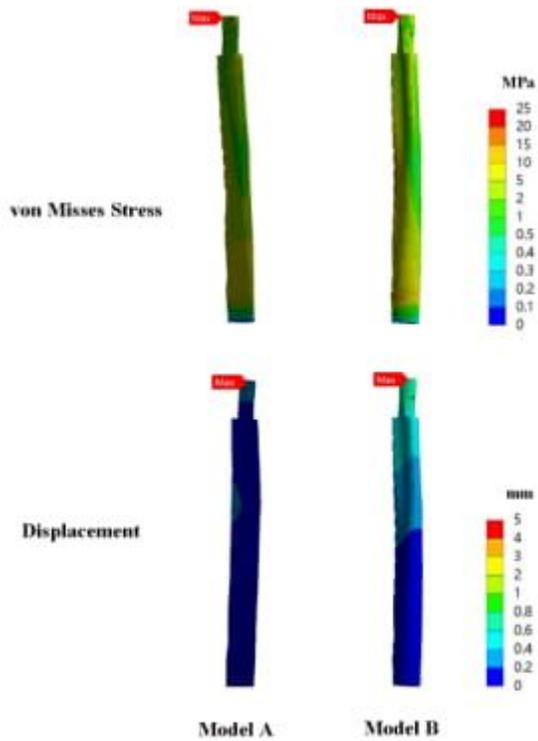


Figure 7

There were no significant differences in VMS and stress distribution of fibular graft in Model B (22.73 MPa) and Model C (23.69 MPa). The maximum displacement at the fibular graft in Model B (0.37mm) was significantly less than that in Model C (0.82mm).