The Biomechanical Role of the Fibula in Lower Limbs: A Fracture Mechanics Analysis

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Abstract

Background

Fibular grafting is widely used in the treatment of various bone nonunions and defects because of its good therapeutic effects. Furthermore, partial fibular resection has been used as a treatment for fibular tumors, injuries, and other conditions. The fibula plays important roles in the biomechanics of the lower limbs. Some experts have used cadaver specimens to study these aspects. In this study, the biomechanical effects of the fibula in lower limbs were researched through mechanics analysis.

Methods

We randomly collected knee joint computed tomography (CT) scans from eight adults, including three left knees and five right knees. The DICOM formatted CT scan images were imported into Mimics software. The tibia and fibula were extracted with the CT-bone function in Mimics software, and 3D models of the tibia and fibula were obtained. Each model was imported into 3-MATIC and LS-DYNA software to smooth the surface, perform meshing, define material properties, and set the failure parameters, interface properties, vertical loads and boundary conditions. The tibial fractures in both models were calculated to evaluate the biomechanical role of the fibula in the lower leg.

Results

The validity of the model was verified, and the fibular load condition was similar to those previously reported. In the model with fibular support, the fracture load of the tibia was 78.27±3.36 KN, the initial fracture time was 0.69±0.01 s, and the complete fracture time was 0.75±0.01 s. The fibula carried approximately 7% of the load on the lower leg. In the fibular defect model, the fracture load of the tibia was 72.71±3.25 KN, the initial fracture time was 0.54±0.02 s, and the complete fracture time was 0.62±0.01 s.

Conclusions

The fibula play an essential biomechanical role in lower limb load-bearing and therefore is worthy of clinical attention. We believe that LS-DYNA can be used as an effective tool for the study of fracture mechanics.

Background

With advances in sports medicine, the biomechanical characteristics of the fibula and its role in maintaining the stability of the knee and ankle joints have received increasing attention[1]. However, the fibula was long generally believed to have a negligible role in lower limb load-bearing, as compared with that of the tibia, and was presumed to be a degenerative remnant of evolution[2]. Partial fibular resection is often used as a treatment for chronic osteomyelitis, fibular tumors and other diseases. Fibular grafting is used to treat various bone defects and nonunion because of its high fusion rate. In recent years, with

the long-term follow-up of lower limb function in patients with fibular defects, morphological changes have been found to occur in the tibia secondarily because of the loss of the fibula[3]. Subsequently, knee weakness, ankle pain and other complications result[4]. These findings suggest that the fibula plays an important biomechanical role in the lower limbs[5].

The mechanical environments of the human fibula and tibia differ greatly[6]. The tibia is designed to translate the compressive load of the whole body weight from two horizontal articular surfaces in the knee to a single horizontal surface in the heel, and to support relatively large additional bending and torsion stresses toward the midshaft [7]. In contrast, the fibula is firmly attached to the proximal tibia by ligaments and is free of weight bearing articular surfaces distally. Some studies have indicated that the fibula contributes a substantial ability to resist axial loading[8–9]. The contribution of the fibula to supporting axial loads is influenced by the complexity of the usual loading patterns and its anatomical relationships with the tibia [3]. Some experts believe that the fibula's contribution to total load may be 11–25% in humans[9]. All the above studies were concluded through statistical analysis or biomechanical testing of cadaver specimens. To date, studies of the bone and related biomechanics have mainly focused on the static analysis of bone mass and strength, whereas studies combining fracture mechanics,

i.e., bone trabecular microinjury-crack propagation-microfracture-fracture remain scarce. Continuous damage mechanics, which can directly analyze the stress and failure processes of components, is a major topic in the field of engineering mechanics. Through a fracture mechanics simulation of tibial fracture under an axial load, this study compared the differences in dynamic processes in tibial fracture with or without fibular support to explore the biomechanical role of the fibula in lower limbs.

Materials And Methods

- We retrospectively collected knee joint CT scans from eight adults who had undergone continuous slice CT scanning at the imaging research center of our hospital between June 2020 and December 2020. Patients were excluded if they had a history of lower limb trauma, severe deformities or any underlying diseases. This study was approved by the institutional review board of our hospital after the patients provided informed consent. The mean age of the patients was 45.96 ± 15.42 years (range: 30–63 years). DICOM-formatted CT scan images for each patient were imported into Mimics software. The separated 3D reconstruction of the bone structures was acquired with a CT bone segmentation operation. Then the 3D model was generated and smoothed with the 3D calculate function to obtain the initial 3D finite element model (Fig. 1).

The 3D finite element model was imported into 3-matic software for meshing. The tetrahedral meshing method was used, with a mesh size defined as 1.5 mm. We derived the normal model and the fibular defect model with the volume mesh from 3-matic. We then imported the model into LS-DYNA. We set the bone tissue structure and articular cartilage according to previously reported findings [10]. The elastoplastic follow-up strengthening model * MAT _ PLASTIC_Kinematic Studio was selected as the

skeleton material. The main material parameters were as follows: density: 1,900 kg/m3, Poisson's ratio: 0.21, elastic modulus: 2.3 GPa, failure strain FS: 0.0204 and solid element Solid164 to simulate the bone.

The data were imported into the large finite element analysis software LS-DYNA to calculate the fracture model of tibial fracture on the basis of the stress-displacement curve relationship. These curves were compared with the fracture lines in the fibular defect model to evaluate fibular support.

The collected data were analyzed in SPSS 25.0 statistical software. The data are represented as mean ± SD. The t-tests were used to compare the data. The threshold for statistical significance was $P < 0.05$.

Results

The study participants included four men and four women between 30 and 63 years of age, with a mean age of 45.96 ± 15.42 years. As shown in Fig. 2, a 3D finite element model of the tibia and fibula was created, which contained 188,011 elements and 272,272 nodes; the fibular defect model contained 165,165 elements and 234,756 nodes. The finite element model of the tibia and fibula was based on the original CT data from patients. During the modeling, operations such as threshold division were automatically completed in Mimics software, with few manual operations, thus avoiding the interference of human factors and better reflecting the fracture situation in patients.

As shown in Table 1, in the normal model, the ultimate tibial load was 78.27 ± 3.36 KN, and in the fibular defect model, the ultimate tibial load was 72.71 ± 3.25 KN. The fibular load accounted for approximately 7% of the tibia (Fig. 3,4), similar to previously reported findings[11]. In the fibular defect model, the ultimate tibial load was 72.71 ± 3.25 KN, which was significantly lower than the 78.27 ± 3.36 KN in the normal model ($P < 0.05$). In the fibular defect model, the initiation time of the tibial crack was 0.54 ± 0.02 s, and the complete fracture time was 0.62 ± 0.01 s, whereas in the normal model, the initiation time of the tibial crack was 0.69 ± 0.01 s, and the complete fracture time was 0.75 ± 0.01 s (Fig. 3,4); the difference was significant ($P < 0.05$). The fracture time of the normal model was significantly longer than that of the defect model, thus indicating that the tibia was more prone to fracture in the absence of the fibula, and the complete fracture occurred more quickly.

Table 1
Comparison of the load, the initiation crack time, and ultimate crack time

Group	Load (KN)#	Initiation crack time(s)#	Ultimate crack time(s)#
Normal model (n = 8)	78.27 ± 3.36	0.69 ± 0.01	0.75 ± 0.01
Fibular defect model (n = 8)	72.71 ± 3.25	0.54 ± 0.02	0.62 ± 0.01
t value*	38.340	59.000	22.808
P value*	0.000	0.000	0.000

*t and *P* are the results of load, initiation crack time and ultimate crack time comparisons between different models.

#For the load, initiation crack time and ultimate crack time, the difference was significant ($P < 0.05$).

We analyzed the stress nephograms of eight pairs of models and drew the following conclusions. As shown in the following stress nephogram (Fig. 3, 4), in both models, the axial load on the tibia appeared to have a stress concentration in the middle and lower third of the tibia. In the normal model, stress concentration also appeared on the tibiofibular contact surface and the distal end of the fibula. In both models, the crack initiation occurred in the middle and lower third of the tibia, and started from the front of the tibia. The crack propagation then followed the Von Mises equivalent stress distribution to complete fracture in the posterior region of the tibia. The crack propagation path and crack strike formed by the two models were essentially the same. The angle between the crack strike and the horizontal line was approximately 30°, forming an approximately concave curve. These findings indicate that under axial load, the middle and lower third of the tibia have the greatest likelihood of fracture and are the part of the tibia most vulnerable to fracture. The presence of the fibula can delay the occurrence of tibial fracture, but after fractures occurred, the presence of the fibula did not affect the direction and expansion of the bone crack. On the basis of the stress-time curves, we also found that the trend of tibial fracture was essentially linear, and was not associated with the presence or absence of fibular support.

Discussion

In recent years, with advances in sports medicine, researchers have paid increasing attention to the biomechanical effects of the fibula. Domestic and foreign researchers have conducted relevant studies on the biomechanical effects of the fibula in lower limbs[9, 11–15]. Zahn RK et al. [9] have demonstrated that in patients with severe osteoporosis, the weight bearing of the fibula is critical, owing to the diminished bone quality in older people. Moreover, the authors confirmed the advantage of an internal fixation method that restores the stability of the distal fibula in patients with osteoporosis with distal fibular fractures. Jabara et al.[11] have explained the importance of the stability of the fibular and

proximal tibiofifibular joint. They have emphasized that neglecting proximal tibiofifibular joint instability may be the reason for the failure of a reconstruction of the posterolateral corner or knee ligament. In studying the proximal tibiofibular joint, Calabro et al.[12–14] have found that the fibula had roles in load-bearing and dispersing the torsion stress on the lower limb. Moreover, patients with proximal tibiofibular joint dislocation have complications such as knee pain and weakness. Alves-da-Silva T et al.[15] have described the kinematics of the proximal tibiofibular joint and its relationship to ankle and knee movements in an exploratory cadaver study.

According to a study by Morin, combined fractures of the distal of tibia and fibula are a common orthopedic injury[16]. Javdan et al.[17] have described that 77.7% of fibular fractures occur together with tibial fractures. However, the necessity of fibular fixation in fibular and distal tibial fractures remains controversial. Strauss et al.[18] have examined the effects of fibular fixation in distal tibialfibular fractures, particularly distal tibial fractures, in both laboratory and clinical settings; their results have verified that fibular fixation is helpful in maintaining tibial fracture reduction. Previous studies have shown that effective fixation of fibular fractures improves the force line after internal fixation of tibial fractures and decreases tibial reduction failure[19–20]. Elhence et al.[21] have recommended fibular fixation for all distal fractures when two fractures are in the same plane, and the tibial fracture is relatively stable. However, Rouhani et al.[22] have concluded that there was no advantage of fixation of the fibula in the treatment outcomes of tibial diaphysis distal third fractures. However, the literature on the application of fracture mechanics to study the biomechanical effects of the fibula in lower limbs is scarce.

In recent decades, researchers have performed many experiments and studies on fracture problems[23–25], thus resulting in the emergence and development of fracture mechanics. At present, finite element analysis is used to study fracture, mainly by considering the mechanism of fracture after external force from falling, and by calculating the Von Mises equivalent stress and combining it with fracture failure criteria. However, the basis for judgment of Von Mises equivalent stress is limited to the starting point of fracture failure, which does not fully reflect the actual fracture situation. LS-DYNA software, the most widely used universal explicit dynamic analysis program worldwide, can simulate various complex problems in the real world and is particularly suitable for solving nonlinear dynamic impact problems of various nonlinear structures. At present, LS-DYNA software is widely used in the field of dynamic analysis, and is even used in the simulation of muscle active response force. Lin et al.[23] have described the influence of regional differences in bone mineral density on hip fracture sites, on the basis of fracture mechanics.

In our research, we found that the fibula carries approximately 7% of the axial load on the lower leg. A study using a biostatic model has found that the fibula bears one-sixth of the weight on the lower leg [9]. The results of Trainotti et al.[11] have shown that the fibula bore approximately 6.4% of the body weight. We believe that the differences in the results were due to differences in measurement methods.

We additionally compared the normal model with the fibular defect model and found that tibias with fibular defects were more prone to fracture, and complete fracture occurred faster. Under axial loading, the fibula can disperse stress and delay the time of tibial fracture, although the presence of the fibula does not affect the location of tibial stress concentration, and essentially does not affect the direction and development of cracks.

In addition, Fan et al.[26] have reported that distal tibial fractures accounted for 37.8% of all tibial fractures. They believed that fractures of the distal tibia typically occurred because of axial and rotational forces on the lower extremity. In our research, this hypothesis was confirmed by the typical distal fracture of the tibia after axial loading.

There were some limitations to this study. In this fracture analysis, only the load vector was set; the simulation of fractures caused by different external forces would be more helpful to understand the mechanism of tibial fracture. In addition, this study performed a mechanical comparison in only middle-aged people with normal bones. Bone mineral density and bone strength can affect the fracture type and stress distribution[27]. Therefore, further study is needed in patients with osteoporosis. More biomechanical studies and related clinical research should be performed.

Conclusion

Because the fibula plays an essential biomechanical role in the lower limbs, more attention should be paid to the fibula and the complications caused by its absence in clinical settings. We believe that fracture mechanics is indispensable in the study of biomechanical interactions between bones and therefore is worthy of further application.

Abbreviations

CT: Computed tomography; DICOM: Digital Imaging and Communication in Medicine; 3-D: Three-dimensional;

Declarations

Acknowledgements

Not applicable.

Authors’ contributions

BS, WDM performed the study, analyzed the data, and drafted the manuscript. DL, JQX and DWW contributed to discussion of data, writing, and editing of the article. TGW and BZ contributed to conception and study design, and editing of the article. All authors read and approved the final manuscript. All authors have read the journal policies and have no issues relating to journal policies. All

authors have seen the manuscript and approved to submit to your journal. The work described has not been submitted elsewhere for publication, in whole or in part.

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Availability of data and materials

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

This study has obtained ethics approval and consent of the ethics committee in our hospital.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no conflict of interest.

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Figures

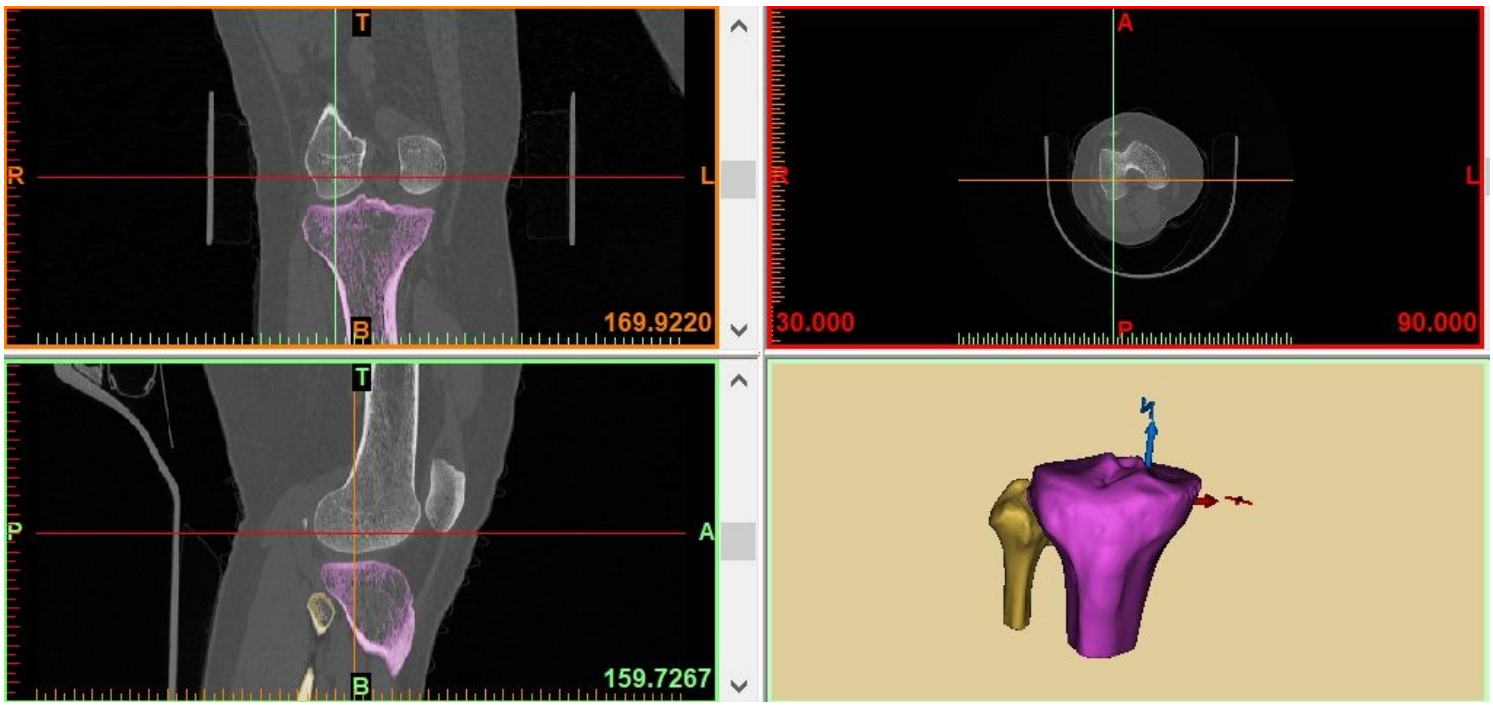

Figure 1

DICOM-formatted CT scan images were imported into Mimics software. The 3D model was created with image CT-bone and calculate 3D.

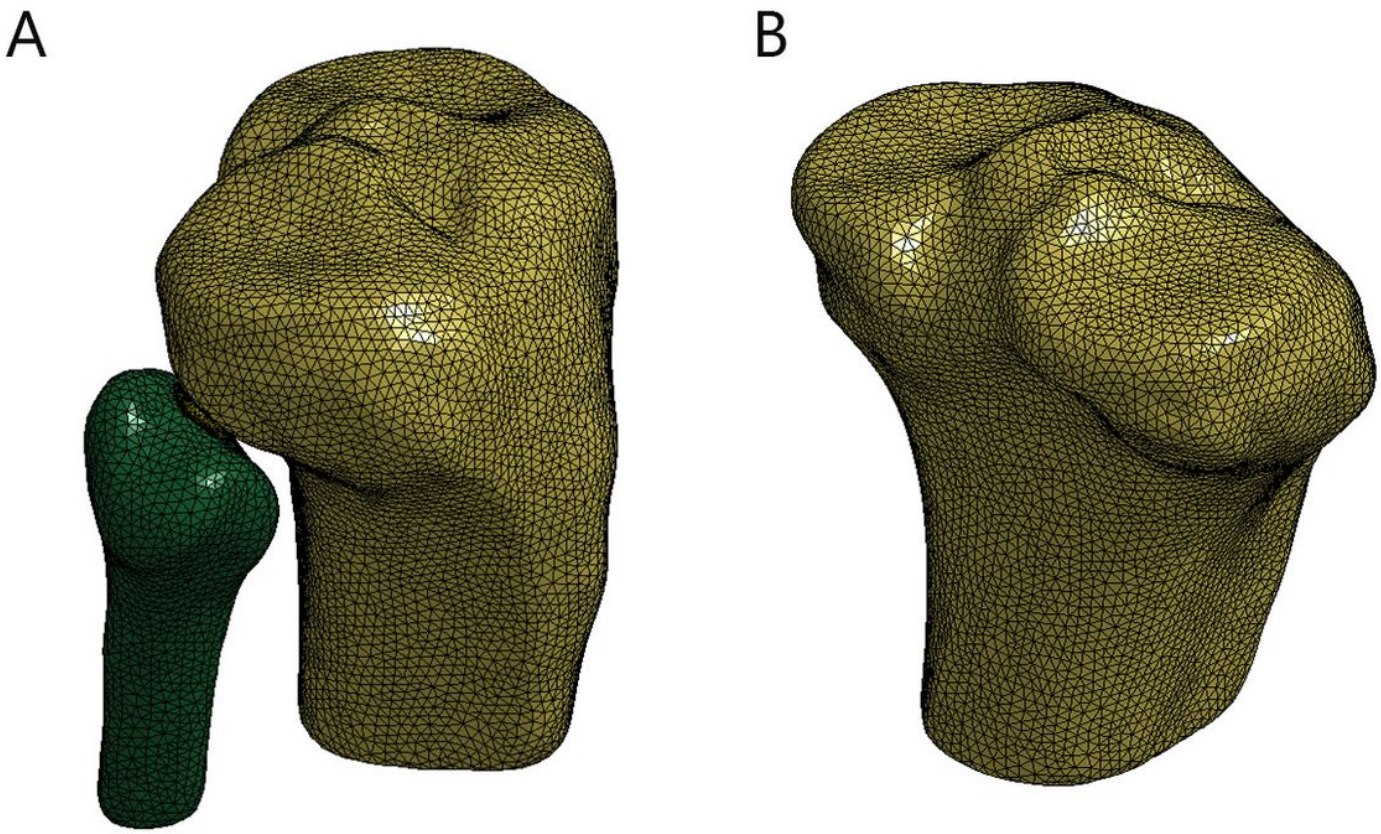

Figure 2

The models with volume mesh. A Normal model. B Fibular defect model.

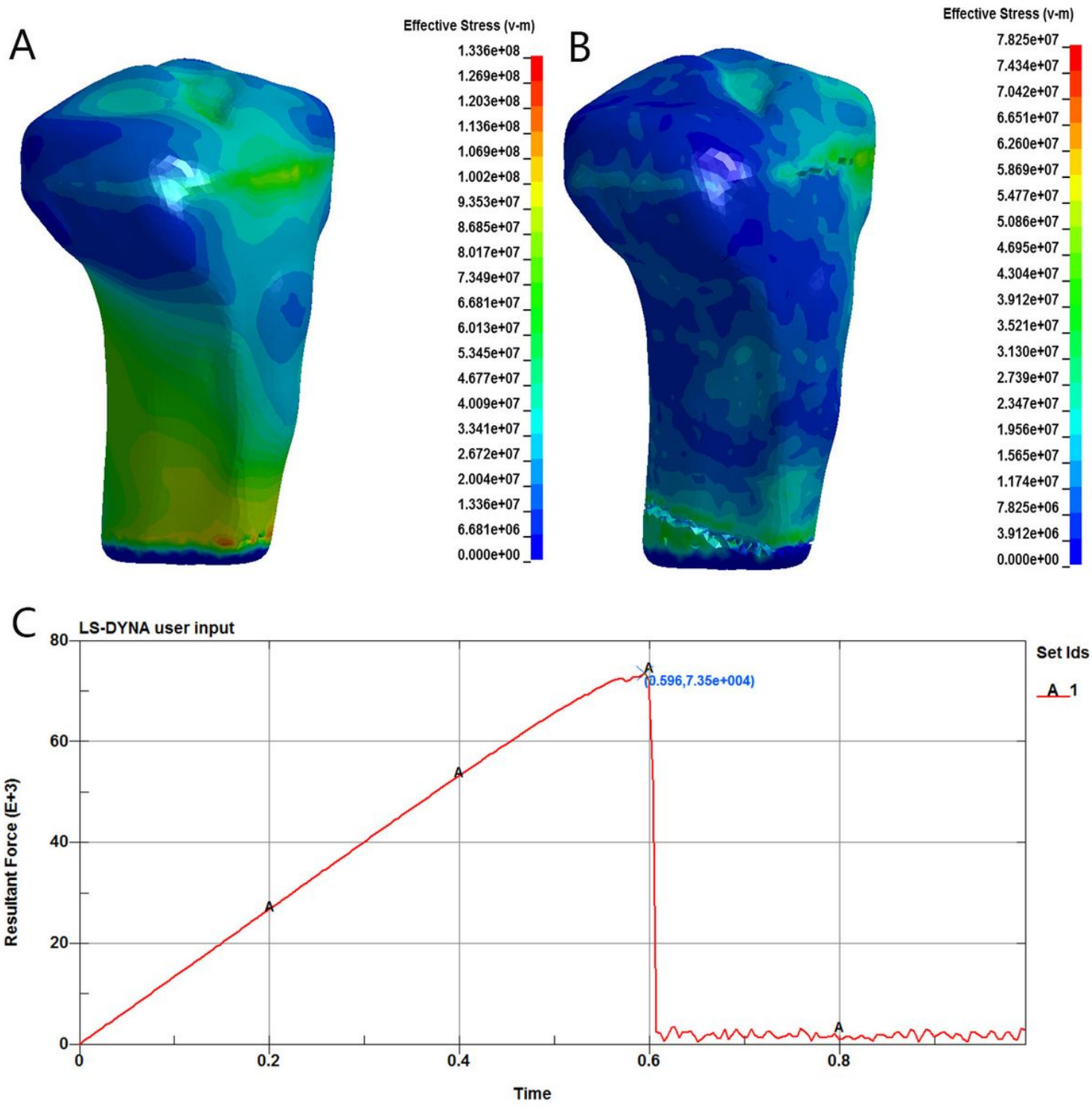

Figure 3

Fibular defect model. A. Stress nephogram of the tibia at the beginning of fracture. B. Stress nephogram of the tibia at complete fracture. C. The fracture load of the tibia was 72.71±3.25 KN, the time of tibial crack initiation was 0.54±0.02 s, and the time of complete fracture of the tibia was 0.62±0.01 s.

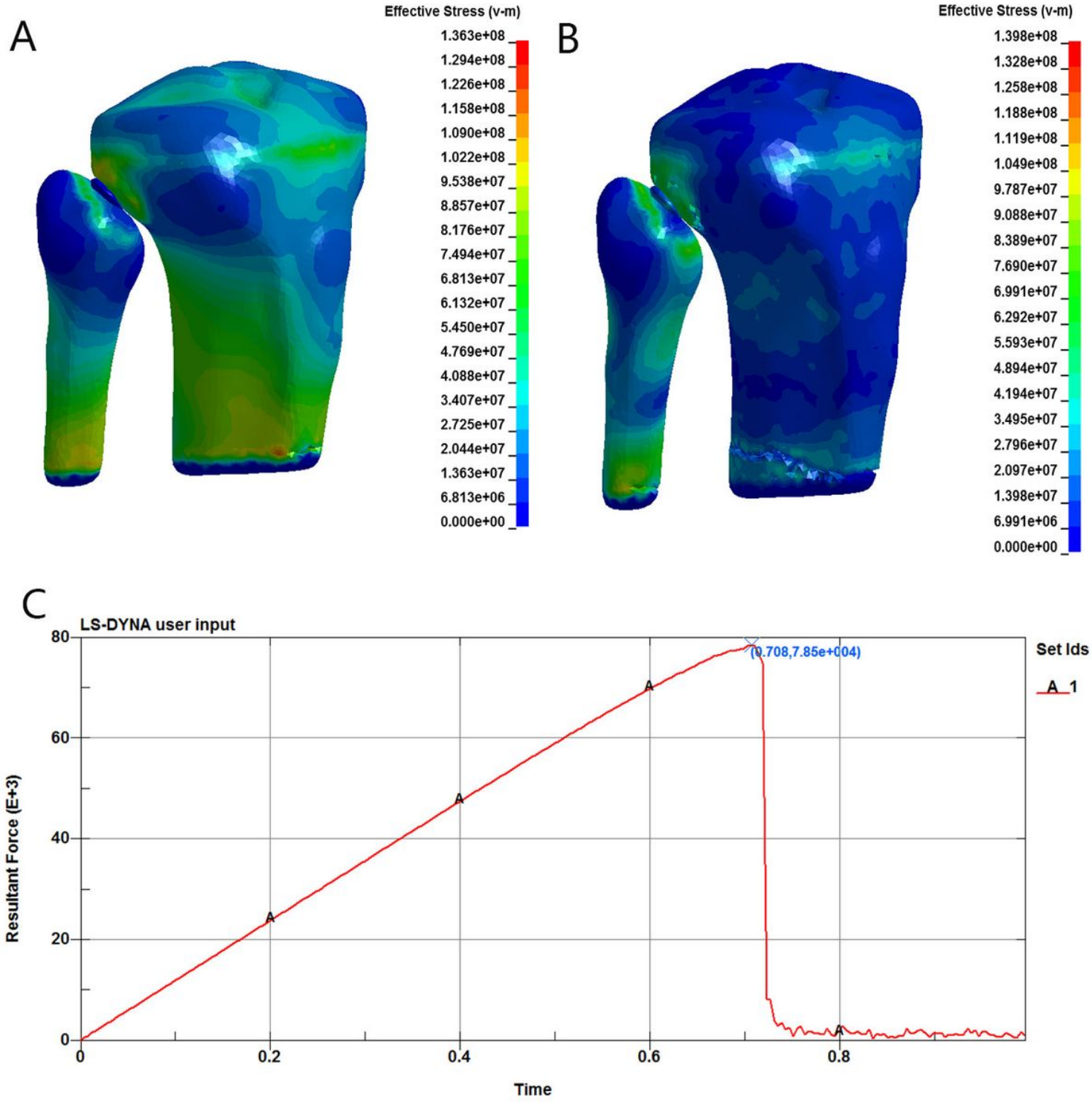

Figure 4

The normal model. A. Stress nephogram of the tibia at the beginning of fracture. B. Stress nephogram of the tibia at complete fracture. C. The fracture load of the tibia was 78.27±3.36 KN, the time of tibial crack initiation was 0.69±0.01 s, and the time of complete fracture of the tibia was 0.75±0.01 s.