Biomechanical Role of Fibula in Lower Limbs: a Fracture Mechanics Analysis

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Research article

Keywords: Fracture mechanics, Fibular defect model, Biomechanics, LS-DYNA software

Posted Date: May 7th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-467009/v1

Abstract

Background Fibular grafting is widely used in the treatment of various bone nonunion and bone defect because of its good therapeutic effect. Besides, partial fibular resection has also been used as a treatment for fibular tumors, injuries, etc. However, fibula plays an important role in the biomechanics of the lower limbs. Some experts have used cadaver specimens to study these aspect. In this study, the biomechanical effects of fibula in lower limbs were researched based on mechanics analysis.

Methods The CT image data of a middle-aged male normal knee joint were selected. The tibia and fibula were extracted by CT-bone function in Mimics software, and the 3D model of tibia and fibula was obtained. The model was imported into 3-matic and LS-DYNA software to smooth the surface, mesh, define material properties, set failure parameters and interface properties, and set 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 fibula load condition was similar to the previous references. In the model with fibula support, the fracture load of the tibia was 78.5KN, the initial fracture time was 0.67164S, and the complete fracture time was 0.73225S. The fibula distributes about 7% of the load on the lower leg. In the fibula defect model, the fracture load of tibia was 73.5KN, the initial fracture time was 0.54034S, and the complete fracture time was 0.61105S.

Conclusions Fibula plays an irreplaceable biomechanical role in the process of lower limb load-bearing, which is worthy of clinical attention. Meanwhile, LS-DYNA can be used as an effective tool for bone fracture and numerical analysis.

Background

With the development of sports medicine, the biomechanical characteristics of fibula and its role in maintaining the stability of knee and ankle joint have been paid more and more attention [1]. However, for a long time, it was generally believed that the fibula played a negligible role in lower limb load-bearing compared to the tibia, and was presumed to be a degenerative remnant of evolution [2]. At the same time, partial fibula resection is often used as a treatment for chronic osteomyelitis, fibula tumor and other diseases. Fibular grafting is also 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 fibula defect, it has been found that morphological changes may occur secondary to the tibia due to the loss of fibula [3]. And there will be knee weakness, ankle pain and other complications [4]. This suggests that 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 can translate the compressive load of the whole body weight, and support relatively large additional bending and torsion stresses toward the midshaft [7]. However, the fibula is firmly attached to the proximal tibia and free of weight bearing articular surfaces distally. Some studies indicate that the fibula contribute transmitting axial load when the body is loaded [8–9]. The contribution of fibula to support axial loads is influenced by the complexity of the usual loading patterns and its anatomical relationships with tibia [3]. Some experts believe that the fibula's contribution to total load could be 11–25% in humans [9]. All the above studies were concluded through statics analysis or biomechanical tests of cadaver specimens.

At present, the study of bone and its biomechanics mainly focuses on the static analysis of bone mass and strength, while the process of combining fracture mechanics: bone trabecular microinjury - crack propagation - microfracture - fracture is still scarce. Continuous damage mechanics, which can directly analyze the stress and failure process of components, is a hot topic in the field of engineering mechanics. Based on fracture mechanics simulation of tibia fracture under axial load, this study compared the dynamic process difference of tibia fracture with or without fibula support to explore the biomechanical role of fibula in lower limbs.

Materials And Methods

The geometry of the intact knee were obtained by Computerized tomography(CT) for bones with the images taken from a 40-year-old healthy male volunteer. The volunteer with the weight of 60kg, the height of 168 cm, the body mass index BMI was 21.3, and neither had lower limb traumatic history nor any underlying diseases. The CT blocks consisted of parallel digital images separated at intervals of 1.5mm in the coronal, axial and sagittal plane with the knee joint at 0° flexion.

The Digital Imaging and Communication in Medicine(DICOM) form data is imported into the Mimics 19.0 software. The separated Three-dimensional(3D) reconstruction of the bone structures was acquired with CT bone segmentation operation. Then the 3D model is generated and smoothed by the calculate function to get the initial finite element model (Fig. 1).

The 3D finite element model was imported into 3-matic software for meshing. The tetrahedral meshing method was adopted, and the mesh size was defined as 1.5mm. Then import the model with the volume mesh into LS-DYNA. We set the bone tissue structure and articular cartilage according to previous reports [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 1900Kg/m^3, Poisson's ratio 0.21, elastic modulus 2.3GPa, failure strain FS 0.0204, and solid element Solid164 was used to simulate the bone.

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

Results

AS shown in Fig. 2, the 3D finite element model of tibia and fibula was created, which contained 188011 elements and 272272 nodes, and the fibula defect model contained 165165 elements and 234756 nodes.

The finite element model of tibia and fibula was carried out based on the original CT data. During the modeling, operations such as threshold division were automatically completed by the Mimics software, with few manual operations, avoiding the interference of human factors and reflecting the fracture situation of patients more truly.

In the normal model, the tibia ultimate load was 78.5KN, and in the fibula defect model, the tibia ultimate load was 73.5KN, and the fibula load accounted for about 7% of the tibia (Fig. 3,4), which was close to some previous references [11]. In the fibular defect model, the ultimate load of tibia was 73.5KN which was significantly lower than that of 78.5KN in normal model. In the fibula defect model, the initiation time of the tibia crack was 0.54034S and the complete fracture time was 0.61105S, while in the normal model, the initiation time of the tibia crack was 0.67164S and the complete fracture time was 0.73225S (Fig. 3,4). The fracture time of the normal model was significantly longer than that of the defect model, which indicated that the tibia was more prone to fracture in the absence of fibula, and the complete fracture occurred more quickly.

According to the stress nephogram (Fig. 3, 4), it was found that in both models, the axial load on the tibia appeared stress concentration in the middle and lower 1/3 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 1/3 of the tibia and started from the front of the tibia. Then, the crack propagation 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 are basically the same. The angle between the crack strike and the horizontal line is about 30°, which is approximately a concave curve, indicating that under axial load, the middle and lower 1/3 of the tibia has the greatest possibility of fracture and is the weakest link of the tibia. The presence of fibula can delay the occurrence of tibial fracture, but once fracture occurs, the presence of fibula does not affect the direction and expansion of bone crack. By observing the stress-time curve, we can also find that the trend of tibial fracture is basically linear, which is not related to the presence or absence of fibula support.

Discussion

In recent years, with the development of sports medicine, scholars have paid more and more attention to the biomechanical effect of fibula. Domestic and foreign scholars have conducted relevant studies on the biomechanical effect of fibula in lower limbs [9, 11–15]. Zahn et al demonstrated that in patients with severe osteoporosis the weight bearing of fibular is critical due to the reduced bone quality in the elderly [9]. Moreover, they confirmed the advantage of an internal fixation method that restores the stability of the distal fibula in osteoporosis patients with distal fibular fractures. Jabara et al explained the importance of the stability of fibular and proximal tibiofifibular joint [11]. They emphasized that neglect proximal tibiofifibular joint instability may be the reason for the failure of an reconstruction of the posterolateral corner or knee ligament. Through the study of the proximal tibiofibular joint, Calabro et al found that the fibula assumed the role of load-bearing and dispersing the torsion stress of the lower limb [12–14]. At the same time, patients with proximal tibiofibular joint dislocation had complications such as knee pain and weakness. Teresa et al described the kinematics of the proximal tibiofibular joint and its relation to the ankle and knee movements by an exploratory cadaver study [15].

According to the study of Morin, the combined fractures of the distal of tibia and fibula is a common orthopedic injury [16]. Javdan et al described that fibular fractures in 77.7% of the cases are common with tibial fractures [17]. However, it's still controversial about the necessity of fibular fixation in fibula and distal tibia fractures. Strauss et al has examined the effect of fibular fixation in cases of distal tibiafibula fractures and particularly in the setting of distal tibia fractures in both laboratory and clinical settings and has verified fibular fixation is helpful to maintaining the tibia fracture reduction [18]. Previous studies have shown that effective fixation of fibula fractures improves the force line following internal fixation of tibial fractures and reduces tibial reduction failure [19–20]. Elhence et al recommended fibula fixation for all distal fractures when two fractures are in the same plane and the tibial fracture is relatively stable [21]. However, Rouhani et al concluded that there was no advantage of the fixation of fibula to the treatment outcome of tibia diaphysis distal third fractures [22]. However, the literature on the application of fracture mechanics to study the biomechanical effects of fibula in lower limbs is rare.

In recent decades, researchers have carried out a lot of experiments and studies on fracture problems [23–25]. This led to the emergence and development of fracture mechanics. At present, finite element analysis is used to study fracture, mainly considering the occurrence mechanism of fracture after falling external force, and by calculating Von Mises equivalent stress and combining with fracture failure criteria. However, the basis for judgment is limited to the starting point of fracture failure, which does not fully reflect the actual fracture situation. LS-DYNA software is the most famous universal explicit dynamic analysis program in the world, which can simulate various complex problems in the real world, and is especially 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, even in the simulation of muscle active response force. Lin et al described the influence of regional difference in bone mineral density on hip fracture site by fracture mechanics [23].

In our research,we found that the fibula carries about 7% of the axial load of the lower leg. A study using a biostatic model has found that the fibula bears 1/6 of the weight of the lower leg [9]. The results of Trainotti showed that fibula bears about 6.4% of body weight [11]. We believe that the differences in the results are due to differences in measurement methods.

At the same time, we compared the normal model with the fibula defect model and found that the tibia with the fibula defect was more prone to fracture and the complete fracture occurred faster. Under axial loading, fibula can disperse stress and delay the time of tibial fracture, but the presence of fibula does not affect the location of tibial stress concentration, and basically does not affect the direction and development of cracks.

In addition, Fan et al described that distal tibial fractures account for 37.8% of all tibial fractures [26]. They believe the fractures of the distal tibia typically occur because of axial and rotational forces on the lower extremity. In our research, this was confirmed by the typical distal fracture of the tibia following axial loading.

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

Conclusion

The fibula plays an irreplaceable biomechanical role in the lower limbs, so more attention should be paid to the fibula and the complications caused by its absence in clinic. At the same time, we believe that fracture mechanics is indispensable in the study of biomechanical interactions between bones, which 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.

Funding

No funding.

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

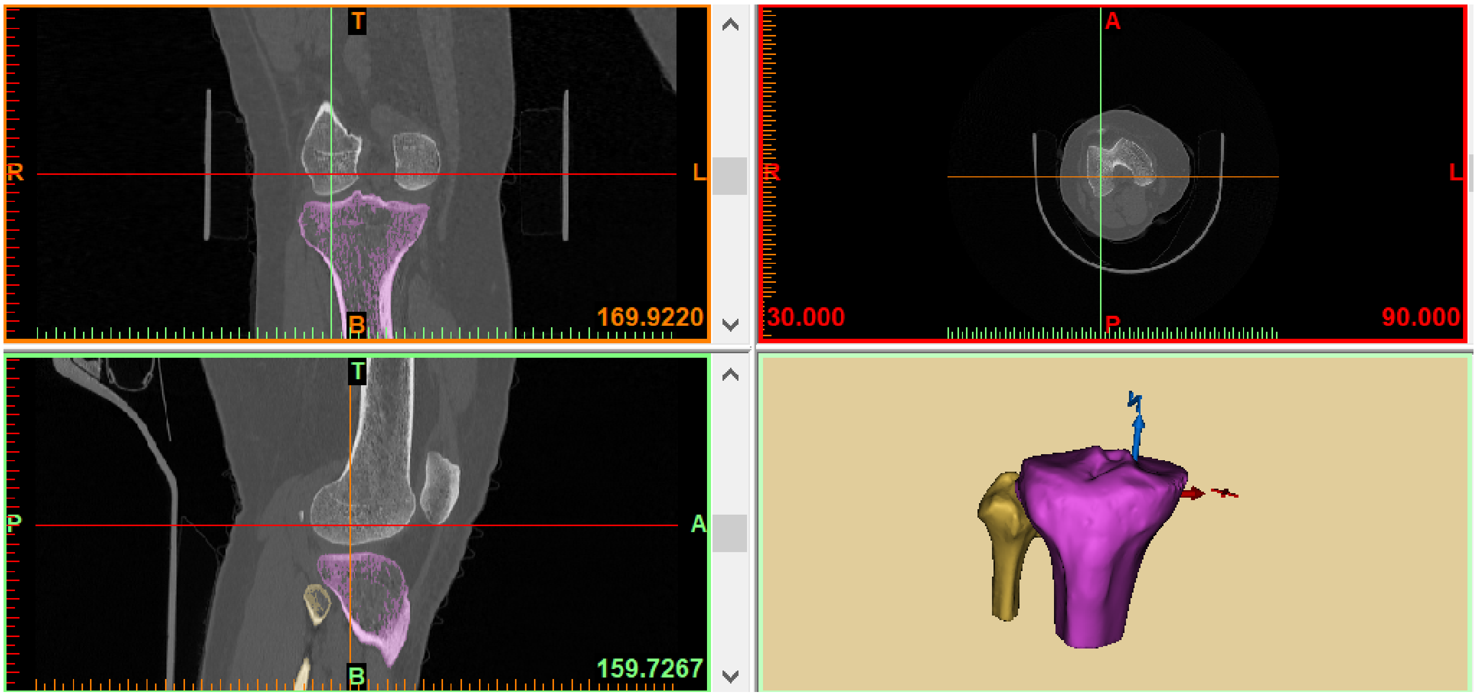

Figure 1

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

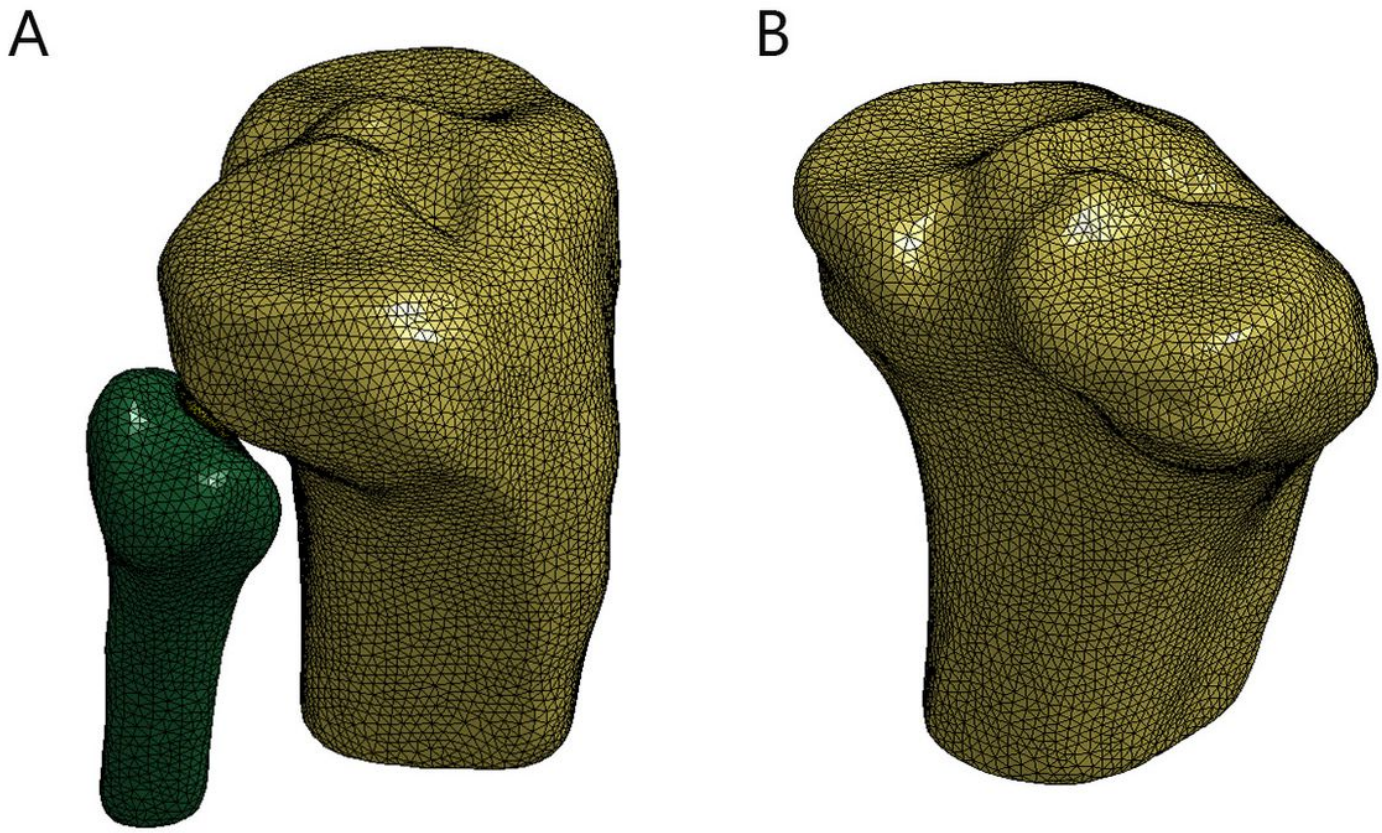

Figure 2

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

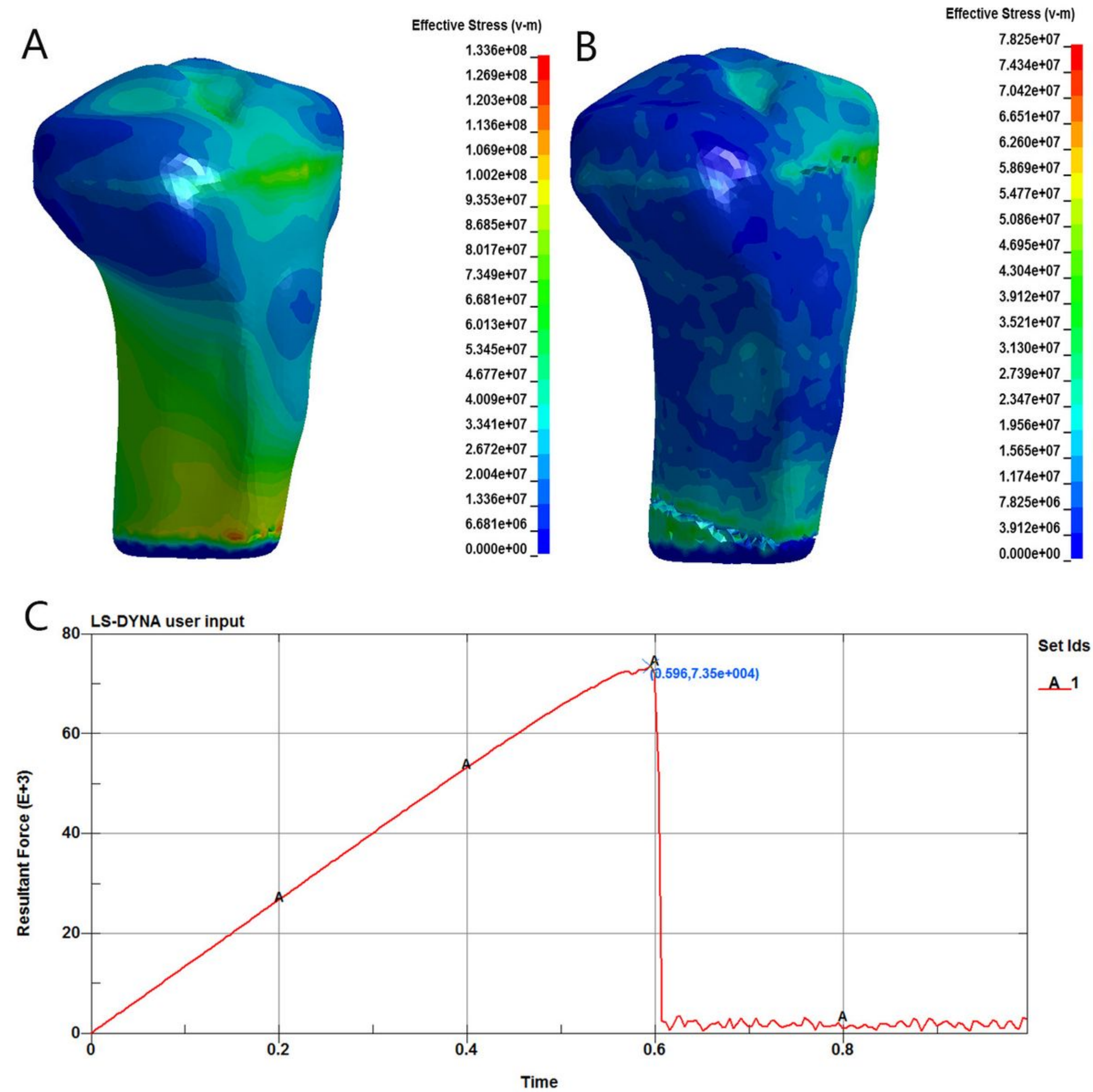

Figure 3

Fibular defect model. A Stress nephogram of the tibia at the beginning of fracture. B Stress nephogram of the tibia at complete fracture. C According to the loading curve, the fracture load of the tibia was 73.5KN, the time of tibial crack initiation was 0.54034S and the time of complete fracture of tibia was 0.61105S.

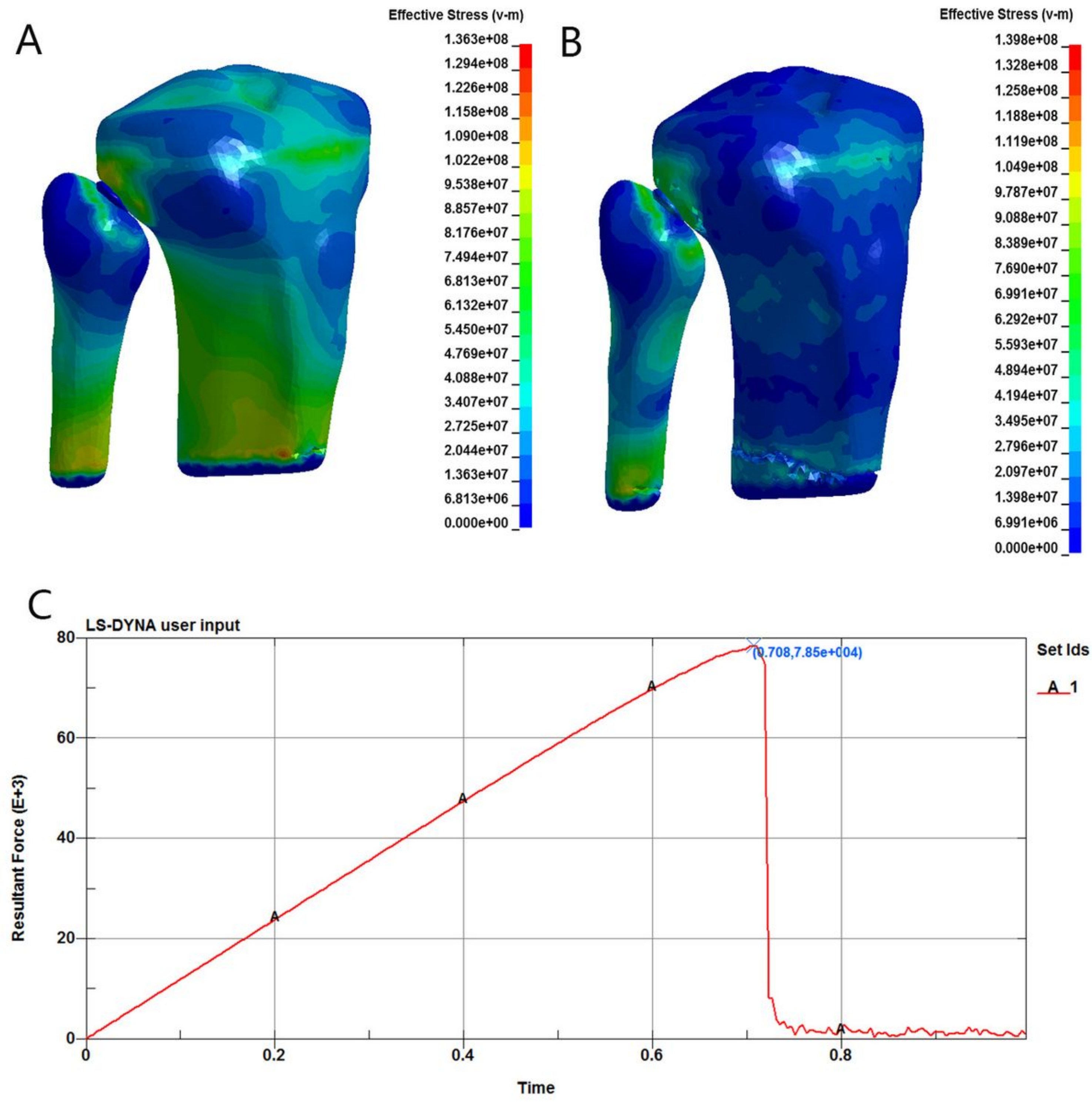

Figure 4

The normal model. A Stress nephogram of the tibia at the beginning of fracture. B Stress nephogram of the tibia at complete fracture. C According to the loading curve, the fracture load of the tibia was 78.5KN, the time of tibial crack initiation was 0.67164S and the time of complete fracture of tibia was 0.73225S.