

## Original Article

# Effect of anterior cruciate ligament rupture of knee joint on meniscus and cartilage: a finite element analysis of knee joint

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Received June 22, 2016; Accepted October 16, 2016; Epub December 15, 2017; Published December 30, 2017

**Abstract:** Objective: To analyze biomechanical changes in organizational structures of the human knee joint before and after anterior cruciate ligament (ACL) rupture using a finite element method (FEM). Method: A three-dimensional finite element model that includes all the main structures of knee joint was constructed. The models were analyzed with backward thrust and varus torque on the femur for stress response using intact and ruptured ACL. Results: Medial meniscus, medial plateau and medial condyle cartilage were found to experience more stress following ACL rupture compared to the lateral compartment, and had higher chances of developing secondary injuries than the lateral structures. High stress regions in the meniscus were mainly located near the posterior horn. In particular, the posterior horn in medial meniscus was a dense area experiencing significant stress. High stress regions in the cartilage surface were mainly in the surface contacting with the tibiofemoral joint. High stress regions in the ligament were mainly around the ligament end. All these highly stressed areas in the structures were coincident with the clinically injury-susceptible positions. Conclusion: FEM is suitable method for knee joint biomechanical analysis. By setting meshing, material properties, constraining conditions and loading, it can provide accurate simulation of stress variations in organizational structures in the knee joint after ACL rupture.

**Keywords:** Knee, biomechanics, finite element analysis

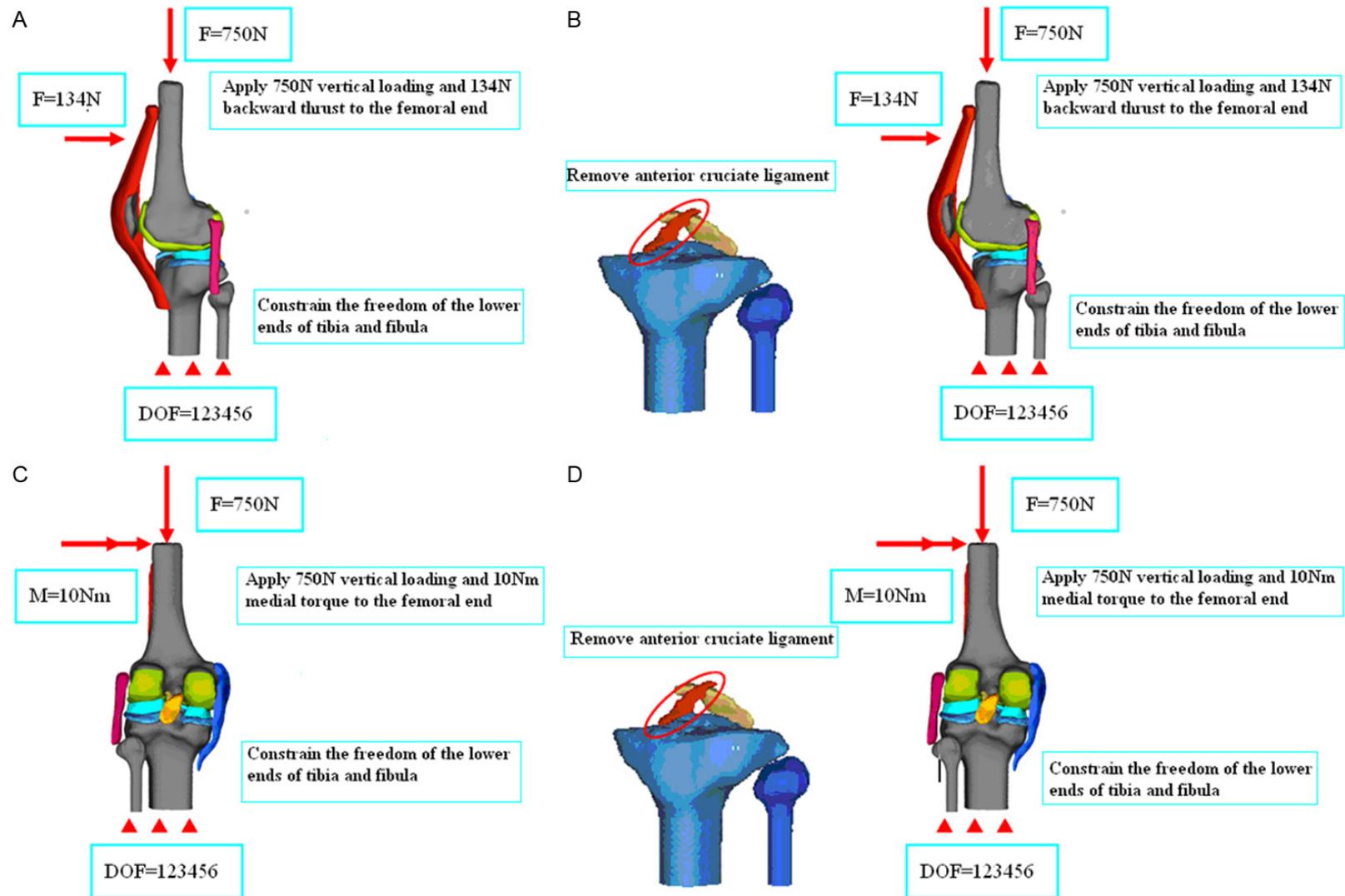
## Introduction

Anterior cruciate ligament (ACL) is an important structure that maintains knee joint stability, and is the most injury-susceptible ligament. With the economic growth in China, and the improvement in people's living standard, the number of patients suffering from traffic and sports injuries is increasing steadily, and the incidence of ACL injury goes up year after year [1].

ACL injury can lead to secondary injuries in the meniscus and cartilage, and early reconstructive surgical treatments have been considered as desirable management options [2]. Although there has been plenty of research on the anatomy, function and treatment of ACL injuries, reports on the position and extent of secondary injuries in the meniscus and cartilage after ACL tear are still rare. In addition, there is a lack of quantitative analysis of knee joint biomechanics following ACL injuries.

Traditional experimental biomechanics research methods have inherent drawbacks, including high cost, difficulty in simulating all conditions, and the inability to obtain domain-wide mechanical distribution information. On the other hand, three-dimensional finite element simulation analysis is an effective method for the mechanical analysis of structures of biological tissues, which present a complex problem with irregular boundary conditions and structural shapes [3]. In this study, high-quality magnetic resonance images were used to construct three-dimensional finite element models that contain all main structures of the knee joint. The introduction of meshing, material properties, constraining conditions and loading allowed relatively accurate simulation of stress variation in the organizational structures in the intact and ACL-ruptured knee joints. These results would provide a better understanding of biological and biomechanical factors affecting meniscus and cartilage injuries after ACL tear.

## Finite element analysis of knee joint



**Figure 1.** Boundary conditions and loadings in intact and ACL-removed models of knee joint. (A) Case 1, (B) Case 2, (C) Case 3, and (D) Case 4.

## Materials and methods

### *Reconstruction of three-dimensional finite element model*

A healthy young male (30 years old, 168 cm/65 kg), who had no previous history of knee joint injury or disease, and had normal organizational structures in the knee joint, as confirmed by X-ray and MRI examinations, was recruited after obtained informed consent. The MRI scanning was carried out when the left knee joint was in a naturally extended and relaxed state, with flexible knee joint surface coil using a SIEMENS 3.0T magnetic resonance scanner. The scanning sequence was as follows: ① Sagittal fat-suppressed two-dimensional T1-weighted gradient echo fast low angle shot (FLASH) sequence: TR/TE=650-695 ms/11 ms, flip angle 60°, matrix: 512×512, sampled 1-2 times; ② Axial fat-suppressed two-dimensional T1-weighted gradient echo FLASH sequence: TR/TE=650 ms/11 ms, flip angle 60°, matrix: 512×512, sampled 1-2 times; ③ Coronal T2-weighted spin echo (SE) sequence: TR/TE=1300 ms /34 ms, matrix: 256×256, sampled 1-2 times. The scanned images were exported and stored as DICOM files. The DICOM files were imported into the MIMICS software, where the DICOM files were showed as two-dimensional images. After importing the two-dimensional image data into the Mimics software, a three-dimensional, solid model of knee joint was reconstructed through point cloud data extraction, pre-treatment and geometric reconstruction. The meniscus, cartilage, and bone structures in the knee joint were considered as rigid structure. Thus, during meshing, bone structures were divided by shell elements. Femoral cartilage, ligament and tibial cartilage were divided using tetrahedral solid elements. The grids were 1 mm in size as full-integral elements. Meniscus was divided using hexahedral solid element with grid size of 1 mm.

### *Finite element analysis*

The simulations were based on the mechanical properties described in previous studies [4-7]; typical mechanical properties of bone, cartilage, meniscus and ligament were used in finite element analysis where bone is much more rigid compared with other soft tissues and their deformation can be neglected. Joint cartilage and meniscus were considered to be linear

elastic materials [4], with bulk modulus of elasticity being 20 Mpa and 59 Mpa, and Poisson's ratio of 0.46 and 0.49 [5, 6], respectively, although they have variable material properties during daily activities such as walking and going up and down stairs when the loading frequency is over 0.1 Hz. Thus, when simulating daily activities, it is considered appropriate and effective simulation to treat these materials as linear elastic materials [5, 6]. All ligaments in this study were simulated as hyperplastic material, which has material constitutive relation of the Neo-Hooke model [7].

### *Contact condition*

The nonlinear contacts were defined in the interaction module as follows: the contact properties between ligament and bone were node-node contact; surface-surface contact was between cartilage and meniscus, with contact property as frictional contact, which had a friction equation with friction coefficient of 0.2 [8]. Since subchondral bone has an elastic modulus at least two magnitudes greater than that of joint cartilage [9], it has no significant impact on calculation and analysis. In order to reduce the complexity, subchondral bone was not defined and was treated as a rigid body that connects at its nodes with the rigid bone body below, as an effective approximation.

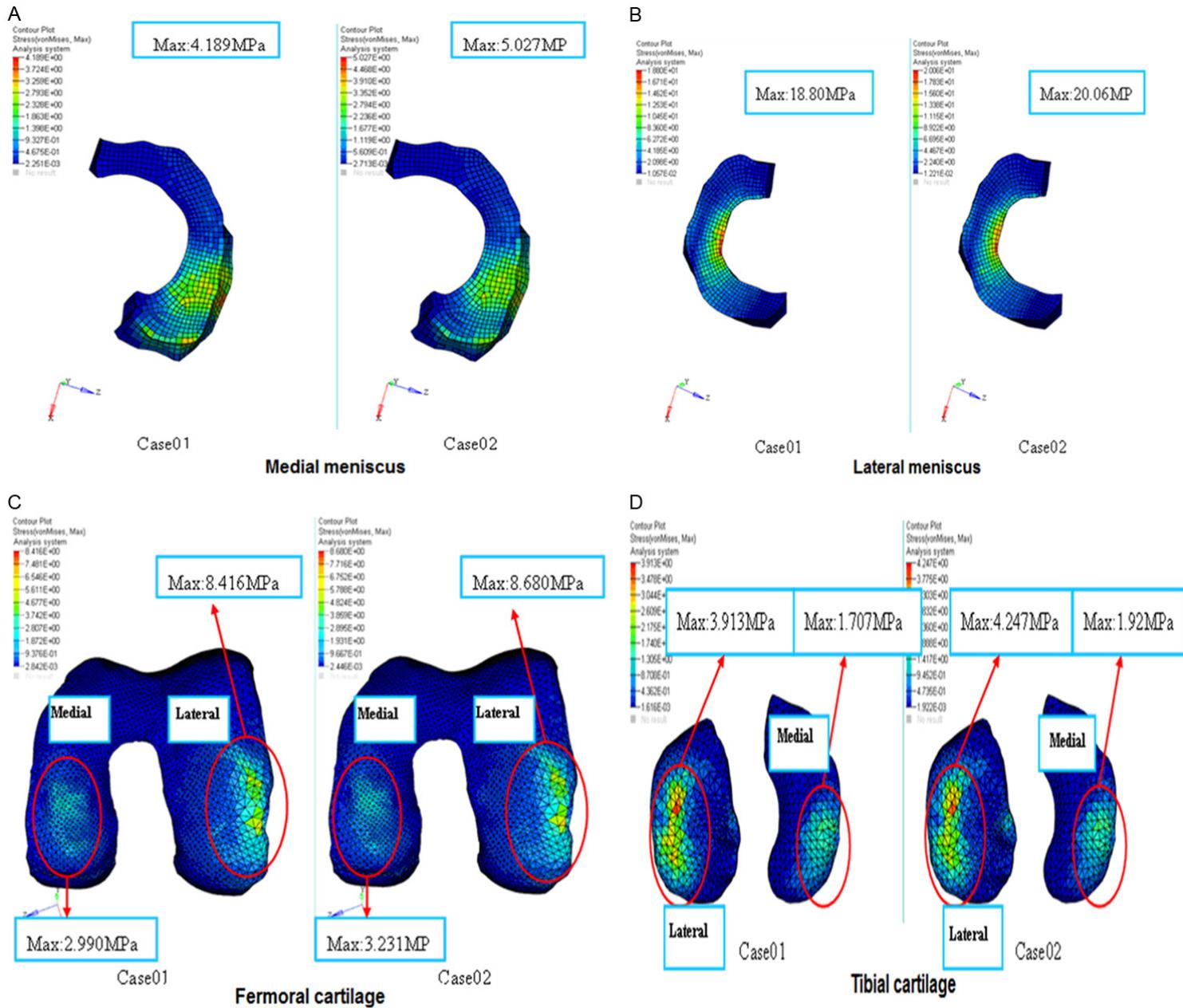
### *Boundary conditions and loading*

The primary objective of this study was to investigate the impact of loss of ACL function on the knee joint. Therefore, loading conditions of femur during backward thrust or varus torque when the knee joint was at a fully extended position were analyzed using a healthy model and an ACL deficient model. In the analysis, the lower surfaces of tibia and fibula were completely fixed, and 750 N vertical loading was applied to the upper surface of femur to simulate the vertical force the joint would have at the fully extended position in a gait cycle. The four cases of boundary conditions and loadings are shown in **Figure 1A-D**.

## Results

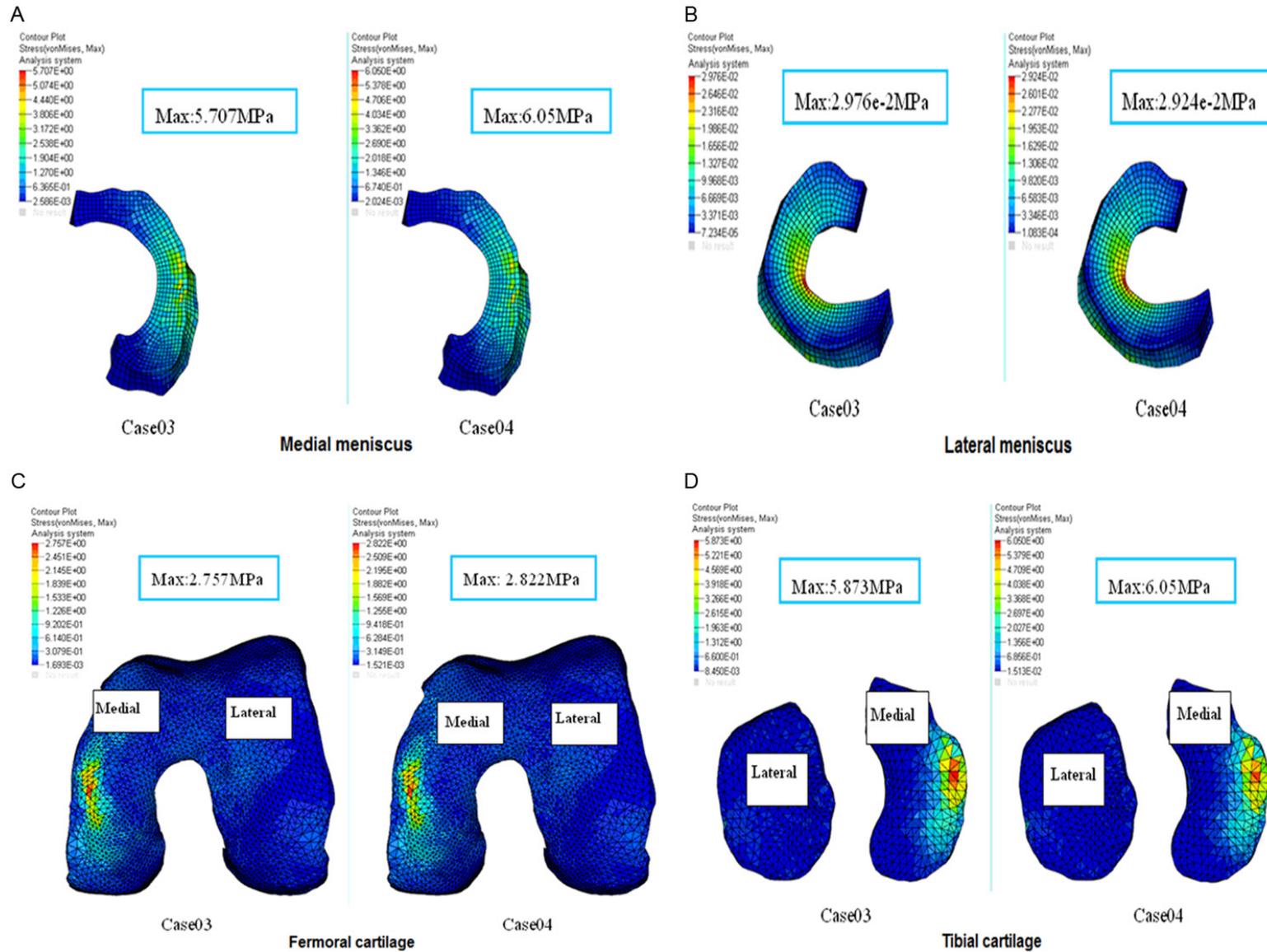
By applying material mechanical properties to the all components of the knee joint, defining boundary conditions of contacts, and applying loading, finite element simulation calculations

# Finite element analysis of knee joint



## Finite element analysis of knee joint

**Figure 2.** Von-mises equivalent stress nephograms of intact and ACL-removed models of knee joint subjected to 750N vertical loading and 134N backward thrust on the femoral end. (A) Medial meniscus; (B) lateral meniscus; (C) Femoral cartilage and (D) Tibial cartilage.



## Finite element analysis of knee joint

**Figure 3.** Von-mises equivalent stress nephograms of intact and ACL-removed models of knee joint subjected to 750N vertical loading and 10Nm medial torque on the femoral end. (A) Medial meniscus; (B) lateral meniscus; (C) Femoral cartilage and (D) Tibial cartilage.

**Table 1.** The peak values of stress (MPa) for components in healthy and ACL-removed knee joint under 750N vertical loading and 134N backward thrust on the femoral end

Knee condition	Medial meniscus	Lateral meniscus	Femur medial condyle cartilage	Femur lateral condyle cartilage	Medial plateau cartilage	Lateral platform cartilage	ACL	Posterior cruciate ligament	Lateral collateral ligament	Medial collateral ligament
Case 01	4.189	18.80	2.990	8.416	1.707	3.913	3.171	8.576	2.426	0.8355
Case 02	5.027	20.06	3.231	8.680	1.920	4.247	-	10.38	2.594	0.9383
Increase	20%	6.7%	8.1%	3.1%	12.4%	8.5%		21%	6.9%	12.3%

**Table 2.** The peak values of stress (MPa) for components of healthy and ACL-removed knee joints under 750N vertical loading and 10Nm medial torque on the femoral end

Knee condition	Medial meniscus	Lateral meniscus	Femur cartilage	Tibia cartilage	ACL	Posterior cruciate ligament	Lateral collateral ligament	Medial collateral ligament
Case 03	5.707	2.976e-2	2.757	5.873	4.426	8.345	6.692	1.315
Case 04	6.050	2.924e-2	2.822	6.050	-	8.649	7.204	1.396
Increase	6.0%	-1.7%	2.3%	3.0%		3.6%	7.7%	6.2%

were achieved with the ANSYS/LS DYNA software to compare the variations of internal stress in the healthy and ACL function deficient knee joints. The results are shown in **Figures 2** and **3** as Von-mises equivalent stress nephograms and **Tables 1** and **2**.

We first determined the peak values of stress when the joints were subjected to 750N vertical loading and 134N backward thrust on the femoral end. The data showed that the peak values of stress in the ACL-removed joint were 3.1% to 21% greater than the peak values of stress in the healthy knee joint (**Figure 2; Table 1**).

We then calculated the peak stress of the healthy and ACL-removed knee joints when subjected to 750N vertical loading and 10Nm medial torque on the femoral end, the results are shown in **Figure 3** and **Table 2**. Compared with the healthy joint, ACL-removed joint had slightly higher peak values of stress for most components (between 2.3% and 7.7%) except for the lateral meniscus.

### Discussion

Our results showed that ACL rupture would lead to increased stress, particularly in medial meniscus, medial plateau and medial condyle

cartilage, resulting in a higher risk of secondary injury compared with the lateral components; the highly stressed regions in meniscus were mainly in the tissues towards the posterior horn, especially at the medial meniscus posterior horn; the highly stressed regions in the cartilage surface were mainly in the tibiofemoral joint contact surface; the highly stressed regions in the ligament were mainly around the ligament end. All these high stress areas in the structures were largely consistent with the clinically injury-susceptible positions [10, 11], suggesting that our simulation is clinically meaningful.

When applying 750N vertical loading and 134N backward thrust on the femoral end, the calculations showed that, under these conditions, lateral meniscus and lateral tibiofemoral cartilage were under higher stress than the medial components. Nevertheless, when subjected to ACL deficient condition, the stress on all knee joint structures increased in comparison with normal knee joint, and the increase was more remarkable in the medial than in the lateral meniscus, and in the medial than in tibiofemoral joint cartilages. The stress on ligament structure was also increased up to 20% in posterior cruciate ligament. When applying 750N vertical loading and 10 Nm medial torque on the femoral end, the calculations showed that

stress was mainly accumulated at medial meniscus and medial tibiofemoral joint cartilage. In comparison with the normal knee joint, ACL deficient knee joint had higher peak stress in most compounds, particularly in lateral collateral ligament (7.7%). Previous studies show that increased stress is an important factor of secondary damages in meniscus and cartilage [12-14].

Joint cartilage and meniscus have very complex material properties with present non-linear mechanical behavior. In the present study, joint cartilage and meniscus were defined as linear elastic material because they are in the elastic response phase in daily activities and be simulated as linear elastic material [5, 6]. All ligament simulations in this study adopted the Neo-Hooke model as material constitutive relation [7]. This is because ligament tissue has non-linear, highly viscoelastic and anisotropic material characteristics, and its constitutive model is extremely complicated and difficult to be presented with accuracy. The constitutive model used in this study under existing restrictions of experimental conditions was based on classical material mechanical property presentation used in previous research results.

The boundary conditions and loadings were selected for better comparisons with the stress distribution reported previously [8, 10, 15]. The lower surfaces of tibia and fibula were completely fixed and applied 750N vertical loading to the femur upper surface, to simulate the vertical forces of the human knee joint in a completely extended position when standing on one foot. The biomechanics function of ACL is to mainly restrict tibia moving forward and knee joint inversion. Therefore, our simulations included femur backward thrust and varus torque when the human knee joint was at a fully extended position.

This study was based on source data from 3.0T high-precision MRI scanning. The constructed model consisted of all main soft and hard tissue structures of the knee joint, with realistic shapes and intact structures. The geometric similarity was substantially improved compares with previously constructed models. The model finite element analysis used the Ansys-Lsdyne system, which has good non-linear analysis function. When defining ligament material properties, non-linear constitutive model was used

for the simulation. These improved the model's mechanical similarity. As a result, the data obtained from this study is consistent with those obtained from clinical epidemiological studies [16, 17], suggesting that to some extent the finite element analysis is appropriate.

However, there are some limitations regarding the study outcomes. First of all, effects of certain structures, such biceps femoris, semitendinosus, semimembranosus and articular capsule on knee joint stress were not included and analyzed, which may result in stress response as compared to the actual situation. Secondly, in the finite element analysis, simplification and approximation were adopted to certain extent on the material mechanical properties of bone, cartilage and meniscus as elastic materials, which in the reality, all tissues are non-linear, anisotropic and viscoelastic. This is still an insurmountable obstacle of finite element analysis at present. Therefore, further research on the mechanical properties of biological tissues is required for better simulation and analysis [18]. We believe with further development in material science, finite element analysis theory and computer science, three-dimensional finite element simulation analysis of the knee joint will no doubt become a major method for knee joint biomechanics analysis.

### Acknowledgements

This study was supported by Henan Science and Technology Research Project (1421023-10183).

### Disclosure of conflict of interest

None.

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## Finite element analysis of knee joint

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