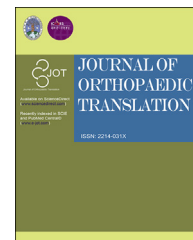


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ORIGINAL ARTICLE

Effect of degenerative and radial tears of the meniscus and resultant meniscectomy on the knee joint: a finite element analysis

Kaijia Zhang ^{a,1}, Lan Li ^{a,b,f,1}, Longfei Yang ^b, Jianping Shi ^c,
Liya Zhu ^c, Huixin Liang ^d, Xingsong Wang ^b, Xianfeng Yang ^{e,**},
Qing Jiang ^{a,f,*}

^a State Key Laboratory of Pharmaceutical Biotechnology, Department of Sports Medicine and Adult Reconstructive Surgery, Drum Tower Hospital Affiliated to Medical School of Nanjing University, Nanjing, China

^b School of Mechanical Engineering, Southeast University, Nanjing, China

^c School of Electrical and Automation Engineering, Nanjing Normal University, Nanjing, China

^d School of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China

^e Department of Radiology, Drum Tower Hospital Affiliated to Medical School of Nanjing University, Nanjing, China

^f Institute of Medical 3D Printing, Nanjing University, Nanjing, China

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KEYWORDS

Compressive stress;
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analysis;
Meniscal tear;
Meniscectomy;
Shear stress

Abstract *Objective:* The objective of this study is to investigate the biomechanics on the knee components caused by degenerative and radial meniscal tears and resultant meniscectomy.

Methods: A detailed finite element model of the knee joint with bones, cartilages, menisci and main ligaments was constructed from a combination of computed tomography and magnetic resonance images. Degenerative and radial tears of both menisci and resultant medial meniscectomy were used and two different kinds of simulations, the vertical and the anterior load, mimicking the static stance and slight flexion simulations, were applied on the model. The compressive and shear stress and meniscus extrusion were evaluated and compared.

Results: Generally, both degenerative and radial tears lead to increased peak compressive and shear stress of both cartilages and menisci and large meniscus extrusion, and the medial meniscal tear induced larger value of stress and extrusion than the lateral meniscal tear. The peak

* Corresponding author. Department of Sports Medicine and Adult Reconstructive Surgery, Drum Tower Hospital Affiliated to Medical School of Nanjing University, Nanjing, China.

** Corresponding author.

E-mail addresses: xianfeng9807@163.com (X. Yang), qingj@nju.edu.cn (Q. Jiang).

¹ Kaijia Zhang and Lan Li are co-first authors, they contributed equally to the work.

stress and meniscus extrusion further elevated after the medial meniscus meniscectomy. Distribution of stress was shifted from the intact hemi joint to the injured hemi joint with either medial or lateral meniscal tear.

Conclusion: Our finite element model provides a realistic three-dimensional knee model to investigate the effects of degenerative and radial meniscal tears and resultant meniscectomy on the stress distribution of the knee. The stress was increased in meniscal tears and increased significantly when meniscectomy was performed. Increased meniscus extrusion may explain the mechanism for higher stress on the components of the knee.

The translational potential of this article: Meniscal tears are the most common damage associated to the menisci, and meniscectomy is often performed to relieve the pain and instability of the knee. The results of our study indicated increased stress on cartilages and menisci, which may lead to early onset of osteoarthritis. This may guide surgeons to preserve more of the meniscus when performing meniscectomy.

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Introduction

The menisci are two crescent-shaped discs of fibrocartilage that are located between the surfaces of the femur and tibia in the medial and lateral compartments of the knee joint. The major components in the meniscus are water, collagen and proteoglycans and have the ability to resist tension, compression and shear stress [1]. The main functions of the menisci are load transmission to a large area of the articular cartilage, shock absorption during dynamic movements and stability of the knee joint. Meniscal tears are the most common damage associated to the menisci, with the prevalence of approximately 0.16% incidences per year [2]. Degenerative meniscal tears tend to occur in patients over the age of 40 years and are usually asymptomatic in the early stages. The degenerative tears are complex tears combined with horizon cleavage and partial defect and have high prevalence at the middle-posterior segment of the meniscus. It has been reported that more than 50% of patients with degenerative meniscus tears do not have knee symptoms [3]. Besides, radial tears, usually lining vertical to the edge and extending to the periphery, are considered less common than other types of meniscal tears and can impair the function of the meniscus, leading to increased wear and degenerative changes in the affected joint [4]. These tears of the meniscus can significantly affect the load transmission and shock absorption function of the menisci and thus cause changes to the biomechanical loading of the knee joint [5]. Such tears are not considered to be repairable, and, thus, meniscectomy, the removal of the damaged, unstable portion of the meniscus, is often performed to relieve the pain and instability of the knee joint. However, meniscectomies have been reported to induce higher levels of contact stress on both cartilages and menisci [6]. In addition, knee osteoarthritis, a common ailment that limits activity and causes significant functional decline in the elderly, is often a result of increased biomechanical loading that induces a pathological response in joint tissues [7]. Hence, the mechanism of the load transmission of the knee joint after degenerative or radial meniscal tears and resultant meniscectomies needs to be investigated.

With respect to load transmission analysis, finite element (FE) simulation could provide detailed magnitudes and graphical illustrations on stress to the knee joint after meniscal tears and resultant meniscectomies. Different models, including two-dimensional (2D) and three-dimensional (3D) models of the knee joint have been constructed to investigate the biomechanical changes to the knee joint after meniscal tears. Wilson et al. [8] and Vadher et al. [9] developed 2D knee joint models and determined that meniscectomies increased contact stress on the cartilages. However, a real knee joint is very complex, and a 2D FE model cannot represent the true mechanical changes of the knee. 3D FE models were then developed to study these changes after meniscectomy [10,11]. The models were required to have bones, cartilage layers, menisci and constructed ligaments to replicate the stress distribution along the knee joint. To our knowledge, there are few studies that have reported the effects of degenerative and radial meniscal tears and resultant meniscectomy on the stress changes and load redistribution of the knee joint.

The main purpose of the present study was to construct an elaborate 3D FE model of the knee joint including bones, cartilages, menisci and main ligaments. This was then used to investigate the biomechanics of the knee components caused by degenerative and radial meniscal tears and resultant meniscectomy. Two different kinds of simulations, the vertical and the anterior load, mimicking the static stance and slight flexion simulations, were applied on the model, and then the compressive and shear stresses of the components were evaluated. The results of this study may help to explain the causes for degeneration of the cartilage and menisci after degenerative and radial meniscal tears and resultant meniscectomy.

Materials and methods

All methods in this study were carried out in accordance with the relevant guidelines and regulations. All experimental protocols were approved by the Drum Tower Hospital affiliated to the Medical School of Nanjing University.

Data acquisition

Magnetic resonance (MR) data were obtained from a 35-year-old male patient using the 3-T clinical MR scanner (uMR 770; United Imaging, Shanghai, People's Republic of China) with a 12-channel knee send–receive radio frequency coil. The patient was in the supine position, and the knee to be examined was positioned in the central region of the coil. A modulated flip angle technique in refocused imaging with extended echo train sequence was performed using two excitations, 176 continuous slices and a slice thickness of 1.5 mm, repetition time 1000 ms, echo time 56 ms, matrix 240*228, field of view 152 mm, and voxel size of $0.67 \times 0.63 \times 0.64 \text{ mm}^3$ was used for sagittal planes. The scan time was 6 min 44 s. Computed tomography was performed using the GE Lightspeed 16 CT equipment (GE Healthcare, CT, USA) on the same individual. The scan was performed on the lower limb at the neutral posture with a slice distance of 0.625 mm and a field of view of 500 mm.

3D reconstruction and construction of the knee joint

The 3D models of bone structure and soft tissues were reconstructed using MIMICS 19.0 (Materialise, Leuven, Belgium). The Digital Imaging and Communications in Medicine (DICOM) image files were imported and segmented on the basis of grey intensities. The separated 3D reconstruction for each bone was performed using the computed tomography bone segmentation procedure. The contours of the articular cartilages (femoral, tibial and patellar), menisci (medial and lateral) and ligaments (medial collateral, lateral collateral, anterior cruciate, posterior cruciate and patellar tendon) were respectively segmented from magnetic resonance imaging images. To minimize variation in the models, the manual segmentation process of bony and nonbony structures was performed under the supervision of an experienced orthopaedist and radiologist, with an accuracy of 0.1 mm.

The degenerative tear occurred at the middle-posterior segment of both medial and lateral meniscus, with an irregular defect of the meniscus at the medial edge. The radial tear was extended from medial to lateral with a length of approximately 60% of the width of the meniscus, also locating at the middle and posterior thirds. To investigate the effect of meniscectomy on the knee joint, the partial meniscectomy models with removal of the damaged portion of the meniscus were developed.

The assembled construction is shown in Figure 1A–C. Degenerative and radial meniscal tears and resultant meniscectomy were constructed using Magics 19.0 (Materialise, Leuven, Belgium) and is shown in Figure 1D and E.

FE modelling and material properties

All data were exported as stereolithography files, and surface remesh was performed using the Materialise 3-matic 11.0 software (Materialise, Leuven, Belgium). The completed models were imported and assembled in Abaqus 2017 (SIMULIA, Rhode Island, USA). As ligaments are nonlinear materials, the quadratic hybrid formulation was

used and the unit type was a 10-node quadratic tetrahedron (C3D10H). For other linear materials, the unit type was a four-node linear tetrahedron (C3D4).

The ligaments were modelled as transverse isotropic nearly incompressible neo-Hookean materials [11–13] with the strain-energy function:

$$\Phi = C_{10}(\bar{G}_{1-3}) + \frac{1}{D_1}(J_F - 1)^2 + S(\lambda) \quad (1)$$

where, $S(\lambda)$ denotes the strain energy function of the fibre family that satisfies the conditions:

$$\lambda \frac{ds}{d\lambda} = \begin{cases} 0, & \lambda \geq 1 \\ C_3(e^{(\lambda-1)C_4-1}), & 1 < \lambda < \lambda^* \\ C_5\lambda + C_6, & \lambda \geq \lambda^* \end{cases} \quad (2)$$

C_{10} is a bulk material constant related to the shear modulus μ ($C_{10} = 2/\mu$), J_F is the Jacobian of the deformation gradient F and \bar{G}_1 represents the first invariant of the left Cauchy–Green tensor $\bar{G}_1 = \text{tr} \bar{F} \bar{F}^T$ with the modified deformation gradient \bar{F} ($\bar{F} = J_F^{-0.33} F$). The stress in the fibres was dependent on the fibre stretch λ . The fibre stretch λ was determined from the deformed fibre orientation a_d , the deformation gradient F and the initial fibre orientation a_0 ($\lambda a_d = F a_0$). Fibres did not support any compressive stresses if they were under compression $\lambda \leq 1$. The stiffness of the fibres increased exponentially when the fibres stretched between 1 and the pre-defined value (λ^*). Beyond this stretch, the fibres straighten and the stiffness increases linearly. The constant C_3 scaled the exponential stress, C_4 was related to the rate of collagen uncramping and C_5 represented the elastic modulus of the straightened collagen fibres. The constant C_6 was introduced to ensure stress continuation at λ^* [$C_6 = (e^{C_4(\lambda^*-1)} - 1) \cdot C_3 - (C_5 \lambda^*)$]. The material constants C_{10} , C_3 , C_4 , C_5 and D_1 , are listed in Table 1.

Bone material behaviour was linear with an elastic modulus (E) as of 7300 MPa and a Poisson's ratio (ν) of 0.3. The articular cartilage and the menisci were composed of a single-phase linear elastic and isotropic material with the following average properties: $E = 15 \text{ MPa}$, $\nu = 0.475$ and $E = 120 \text{ MPa}$, $\nu = 0.45$, respectively [14–17].

Loads and boundary conditions

We included the total tibiofemoral joint to replicate realistic knee joint characteristics, and two FE simulations were designed based on different postures. The boundary conditions were defined as follows: the tibia and fibula were fixed with full degrees of freedom at the lower end nodes, and the femur was unconstrained for all translational and rotational degrees of freedom. All ligaments were rigidly attached to their corresponding bones to simulate bone–ligament attachment. The kinematic constrain was modelled between the femur and meniscus, the meniscus and tibia and the femur and tibia for both the lateral and medial hemi joints. For static stance simulation, a vertical compressive load of 1150 N (two body weights) was applied on the femur at 0 degree of flexion. For the slight flexion simulation, a vertical compressive load of 1150 N and an anterior load of 350 N (sixty percent of body weight), mimicking the force on knee joint during gait cycle

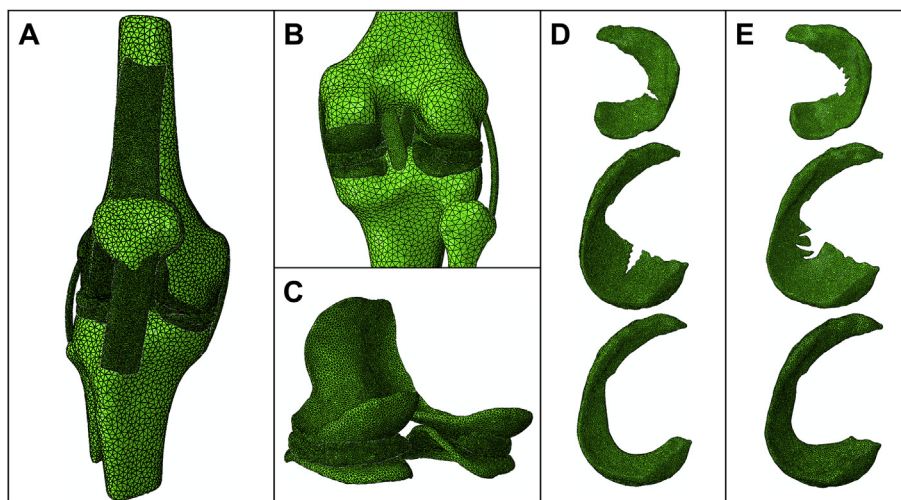


Figure 1 The view of 3D models used in the FE simulation. The general view of the knee joint model (A) the posterior partial enlargement view of knee joint; (B) the rear partial enlargement view of the cartilages and menisci; (C). FE models of meniscal tears and resultant partial meniscectomies; (D) radial tears of the lateral and medial meniscus and resultant partial meniscectomy of the medial meniscus; (E) degenerative tears of the lateral and medial meniscus and resultant partial meniscectomy of the medial meniscus. FE, finite element.

Table 1 Material constants for the ligaments.

Ligaments	C_{10} (MPa)	C_3 (MPa)	C_4 (-)	C_5 (MPa)	D_1 (MPa ⁻¹)	λ^* (-)
ACL	1.95	0.0139	116.22	535.039	0.00683	1.046
PCL	3.25	0.1196	87.178	431.063	0.0041	1.035
LCL	1.44	0.57	48.0	467.1	0.00126	1.063
MCL	1.44	0.57	48.0	467.1	0.00126	1.063
PT	3.25	0.1196	87.178	431.063	0.0041	1.035

ACL = anterior cruciate ligament; LCL = lateral collateral ligament; MCL = medial collateral ligament; PCL = posterior cruciate ligament; PT = patellar tendon.

in daily living activities, was applied on the top and anterior side of the femur at 0 degree of flexion [18,19].

Results

Static stance simulation

Degenerative tear

Under static stance simulation, the compressive and shear stresses were both increased in the post-injured knee joint (Figure 2). For degenerative tear at the medial meniscus, the shear stress was elevated to 1.87 MPa on the femoral cartilage and 1.86 MPa on the tibial cartilage, which were slightly higher than those of the lateral meniscus (Table 2). The compressive stress was 7.73 MPa on the femoral cartilage, which was lower than that of the lateral cartilage. The compressive stress was 6.43 MPa on the tibial cartilage, 22.5% higher than the lateral cartilage (Table 3). For the menisci, lower shear and compressive stresses were observed when the tear occurred at the medial meniscus, compared with the lateral meniscus. After meniscectomy, equal or higher compressive and shear stresses were observed for both cartilages and menisci.

From the nephogram for shear stress (Figure 3), stress shifted from the medial to the lateral component for both the femoral and tibial cartilages for the medial meniscal tear compared with the lateral meniscal tear. The stress on both menisci increased and was focused on the anterior horns (colour increased in redness) for tears at both menisci. After meniscectomy, no significant change to shear stress distribution was observed compared with the medial meniscal tear, with only slight reduction of stress on the medial tibial cartilage. As to compressive stress (Figure 4), similar changes were observed on the menisci similar to shear stress. The stress on both medial and lateral femoral cartilages was higher for the lateral meniscal tear. No significant changes in load distribution were observed for the components.

The extrusion distances of the meniscus are shown in Table 4. The displacement of both menisci increased after injury. In detail, the displacement was larger for the medial meniscal tear, and meniscectomy induced further extrusion compared with the isolated medial tear. When comparing the displacement of the menisci, medial meniscus had an increased amplitude of extrusion compared with the lateral meniscus.

Radial tear

Similar results as degenerative tears were observed for radial tears (Figure 2). Slightly higher shear stress on both cartilages with reduced stress on the menisci was observed, whereas lower compressive stress on the femoral cartilage and menisci and increased stress on the tibial cartilage were observed. Almost all the compressive and shear stresses on both cartilages and menisci were elevated after medial meniscus meniscectomy (Tables 2 and 3).

With regards to nephogram for shear stress (Figure 3), similar changes were found as for degenerative tears. The location for shear stress shifted from the medial to the lateral on both cartilages for medial meniscal tears. Elevated shear stress on the anterior horns of both menisci was observed for tears at both menisci. Meniscectomy had

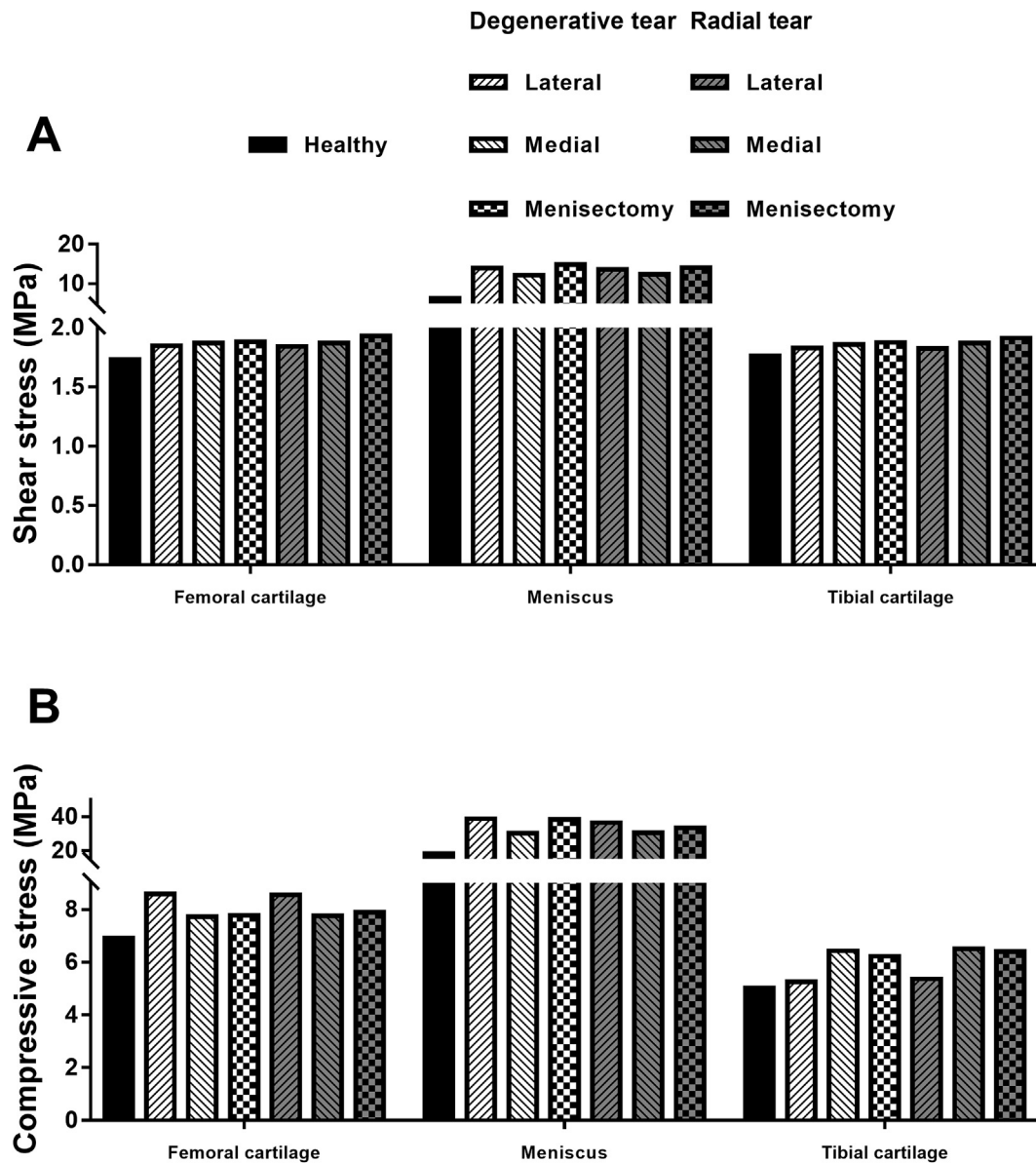


Figure 2 The maximum compression stress and shear stress applied on the knee joint under static stance simulation. (A) The maximum shear stress on the joint; (B) the maximum compressive stress on the joint.

Table 2 Maximum shear stress (MPa) on the joint before and after meniscectomy under static stance simulation.

Structure	Healthy knee	Degenerative tear			Radial tear		
		Lateral	Medial	Meniscectomy	Lateral	Medial	Meniscectomy
FC	1.73	1.85	1.87	1.88	1.84	1.87	1.93
Meniscus	6.35	13.98	12.17	14.93	13.60	12.38	14.10
TC	1.76	1.83	1.86	1.88	1.82	1.87	1.91

FC = femoral cartilage; TC = tibial cartilage.

minimal effects on stress redistribution compared with the medial meniscal tear. The results from compressive stress were also similar to that for degenerative tear (Figure 4). The stress on the femoral cartilage was higher for the lateral meniscal tear, and minimal changes for stress distribution was observed for the other components.

The displacement of both menisci was also increased after injury (Table 4). Similar increased displacement was also observed for medial meniscal tear, with increased extrusion after meniscectomy. Notably, the magnitude of meniscal displacement was greater for the radial tear than for the degenerative tear.

Table 3 Maximum compressive stress (MPa) on the joint before and after meniscectomy under static stance simulation.

Structure	Healthy knee	Degenerative tear			Radial tear		
		Lateral	Medial	Meniscectomy	Lateral	Medial	Meniscectomy
FC	6.92	8.59	7.73	7.78	8.56	7.76	7.90
Meniscus	18.10	38.80	30.25	38.27	36.41	30.56	33.36
TC	5.02	5.25	6.43	6.23	5.37	6.51	6.41

FC = femoral cartilage; TC = tibial cartilage.

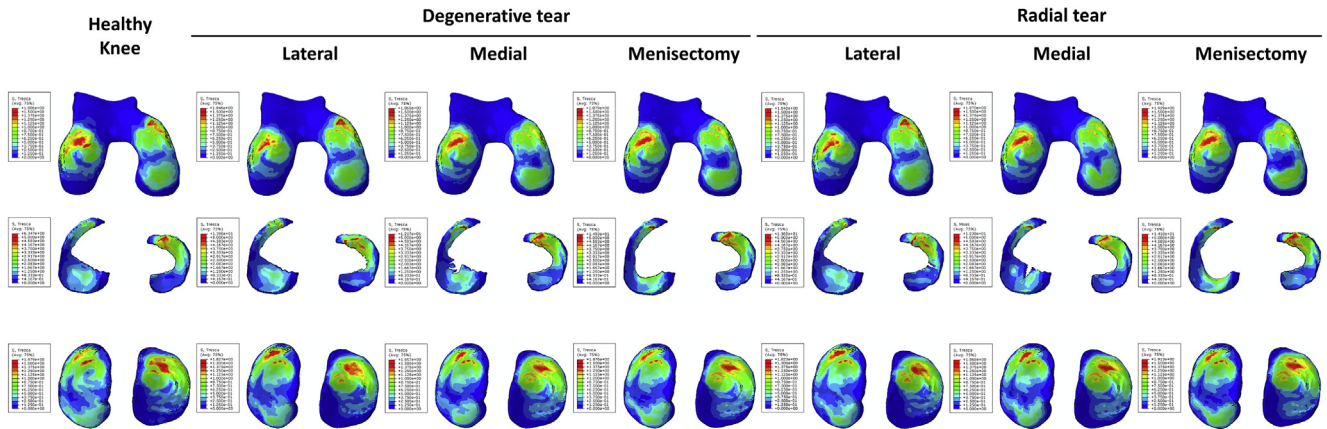


Figure 3 The results of shear stress on the femoral cartilage, menisci and tibial cartilage under static stance simulation. Healthy knee and different types of tears were shown from left to right as the captions indicated.

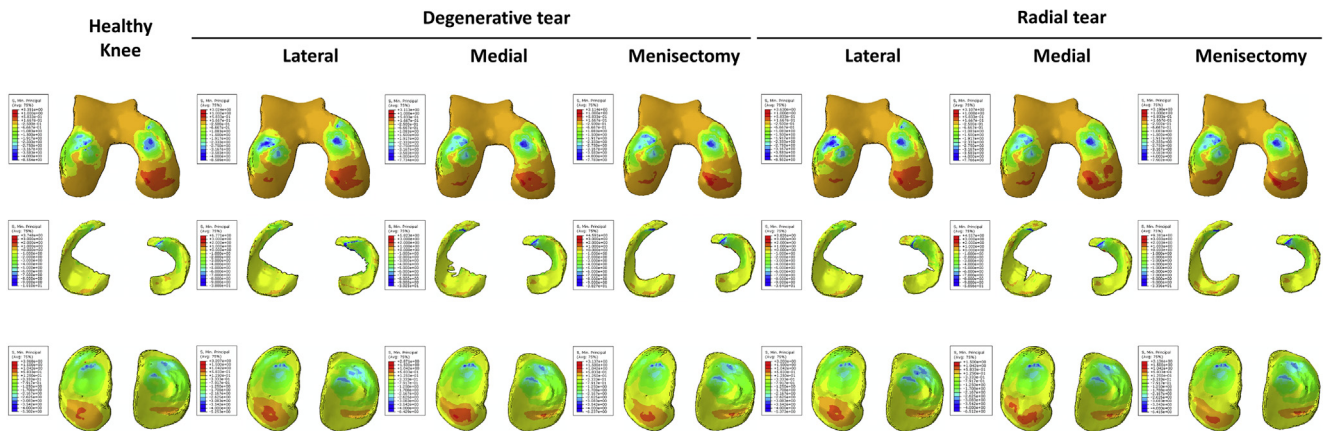


Figure 4 The results of compressive stress on the femoral cartilage, menisci and tibial cartilage under static stance simulation. Healthy knee and different types of tears were shown from left to right as the captions indicated.

Table 4 Meniscus extrusion (mm) under static stance simulation.

Injury	Healthy knee	Degenerative tear			Radial tear		
		Lateral	Medial	Meniscectomy	Lateral	Medial	Meniscectomy
Medial	1.80	1.88	1.93	2.01	1.88	1.99	2.12
Lateral	2.64	2.67	2.70	2.71	2.66	2.70	2.73

Slight flexion simulation

Degenerative tear

To investigate the effect of meniscal tear and resultant meniscectomy on the biomechanical stress distribution

with slight flexion of the knee, an additional anterior force was applied on the model. Different from the static stance simulation, the magnitude of peak shear stress was significantly increased (Figure 5). The peak shear stress on the femoral cartilage was 2.04 MPa for the medial meniscal tear

and 2.12 MPa for the lateral tear, whereas that on the tibial was 3.06 MPa and 2.53 MPa, respectively. The menisci had 15.15 MPa of shear stress after the lateral tear and 12.67 MPa for the medial tear. This increased to 16.25 MPa after medial meniscectomy, reaching 242% compared with no tear. The shear stress on both cartilages had a slight increase (Table 5). For the compressive stress, similar results were observed as the peak compressive stress increased on both cartilages and this increased after meniscectomy. As to the menisci, significant increase was observed after the meniscal tear and meniscectomy induced by higher compressive stress on the menisci (Table 6).

The nephogram for shear stress showed that the posterior shift of the stress on the joint compared with the static stance simulation (Figure 6). For the lateral meniscal tear,

the stress on both cartilages showed a slight shift from the lateral component to the medial. The shear stress on the menisci was significantly located on the edge of the tear, resulting in a larger area of high stress on the lateral meniscus. The medial meniscal tear caused a significant increase in stress distribution on the medial components, including the cartilages and menisci. After meniscectomy, the medial components had a larger area of increased stress, with the peak stress concentrated on the edge of the meniscectomy. The nephogram for compressive stress also showed similar results (Figure 7). The lateral meniscal tear caused a lateral shift of the stress, whereas the medial tear induced additional stress concentrated on the medial part. The medial part of the knee sustained more compressive stress after medial meniscectomy, with most of the stress focussing on the edge of the meniscectomy.

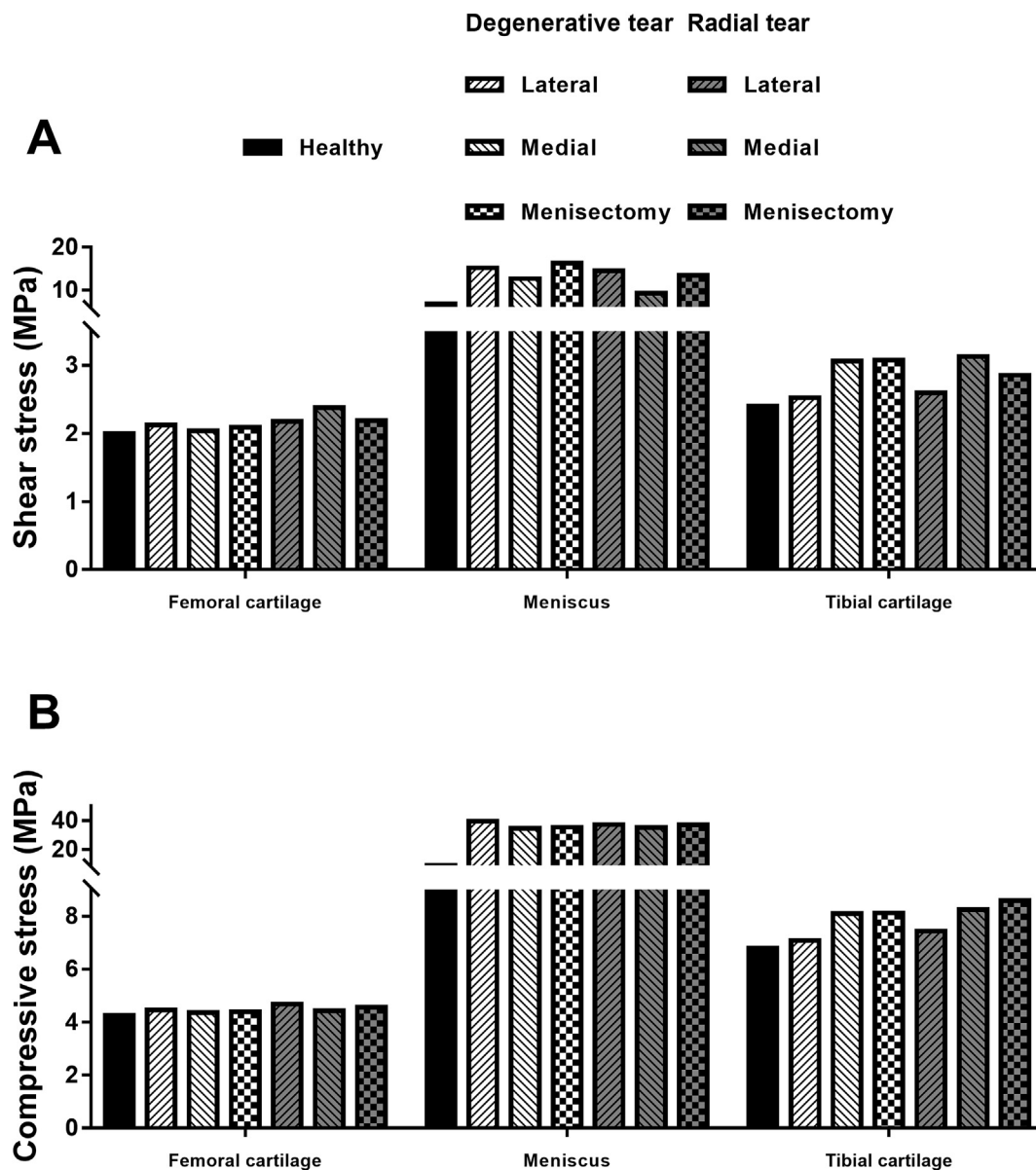


Figure 5 The maximum compression stress and shear stress applied on the knee joint under slight flexion simulation. (A) The maximum shear stress on the joint; (B) the maximum compressive stress on the joint.

Table 5 Maximum shear stress (MPa) on the joint before and after meniscectomy under slight flexion simulation.

Structure	Healthy knee	Degenerative tear			Radial tear		
		Lateral	Medial	Meniscectomy	Lateral	Medial	Meniscectomy
FC	2.00	2.12	2.04	2.09	2.18	2.38	2.19
Meniscus	6.72	15.15	12.67	16.25	14.47	9.22	13.47
TC	2.40	2.53	3.06	3.08	2.59	3.13	2.86

FC = femoral cartilage; TC = tibial cartilage.

Table 6 Maximum compressive stress (MPa) on the joint before and after meniscectomy under slight flexion simulation.

Structure	Healthy knee	Degenerative tear			Radial tear		
		Lateral	Medial	Meniscectomy	Lateral	Medial	Meniscectomy
FC	4.25	4.46	4.36	4.39	4.68	4.42	4.56
Meniscus	9.15	39.41	34.59	35.23	37.12	35.07	36.97
TC	6.81	7.09	8.09	8.12	7.44	8.26	8.59

FC = femoral cartilage; TC = tibial cartilage.

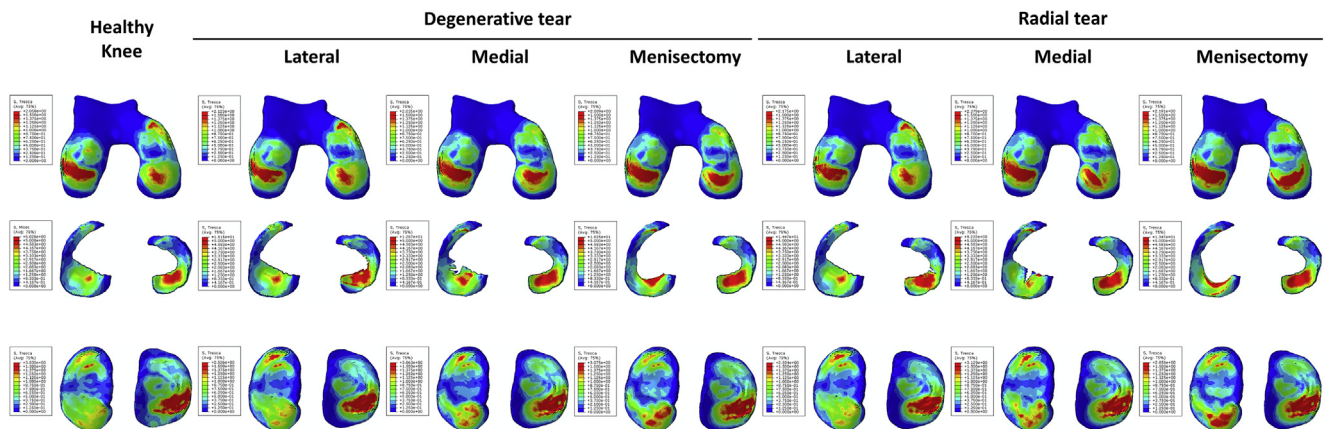


Figure 6 The results of shear stress on the femoral cartilage, menisci and tibial cartilage under slight flexion simulation. Healthy knee and different types of tears were shown from left to right as the captions indicated.

The results for meniscus extrusion under slight flexion simulation are shown in [Table 7](#). The displacement was significantly larger than that under static stance simulation. Both medial and lateral meniscal tears induced a larger meniscus extrusion compared with no tear. Notably, an additional 5% increment in medial meniscus extrusion was noted after meniscectomy compared with an isolated medial meniscal tear.

Radial tear

For radial tear at the medial meniscus, the peak shear stress increased to 2.38 MPa on the femoral cartilage and 3.13 MPa on the tibial cartilage, which is higher than that for the lateral meniscus ([Figure 5](#)). Meniscectomy resulted in significantly elevated stress on the menisci in comparison to the medial meniscal tear ([Table 5](#)). With regards to compressive stress, similar results were observed as radial tears at both meniscus, whereas meniscectomy led to higher compressive stress on both cartilages and menisci ([Table 6](#)).

It was observed from the nephogram of shear stress that the radial tear at the lateral menisci also caused a slight shift of stress from the lateral to the medial meniscus, while the lateral meniscus endured larger shear stress ([Figure 6](#)). The medial meniscal tear caused increased stress on the medial parts of both cartilages and menisci, with most of the medial meniscal stress concentrated on the location of the tear. After meniscectomy, significant increase in stress on the medial parts of both cartilages was observed with stress on the medial meniscus localized on the edge of the meniscectomy. With regards to compressive stress, similar results were observed ([Figure 7](#)). Higher compressive stress was observed at the lateral part after lateral tear, whereas the medial tear and resultant meniscectomy affected a larger area of high stress at the medial part.

Similar results were observed for meniscus extrusion ([Table 7](#)). Both meniscal tears had increased meniscus extrusion. The radial tear at the medial meniscus and resultant meniscectomy resulted in relatively larger

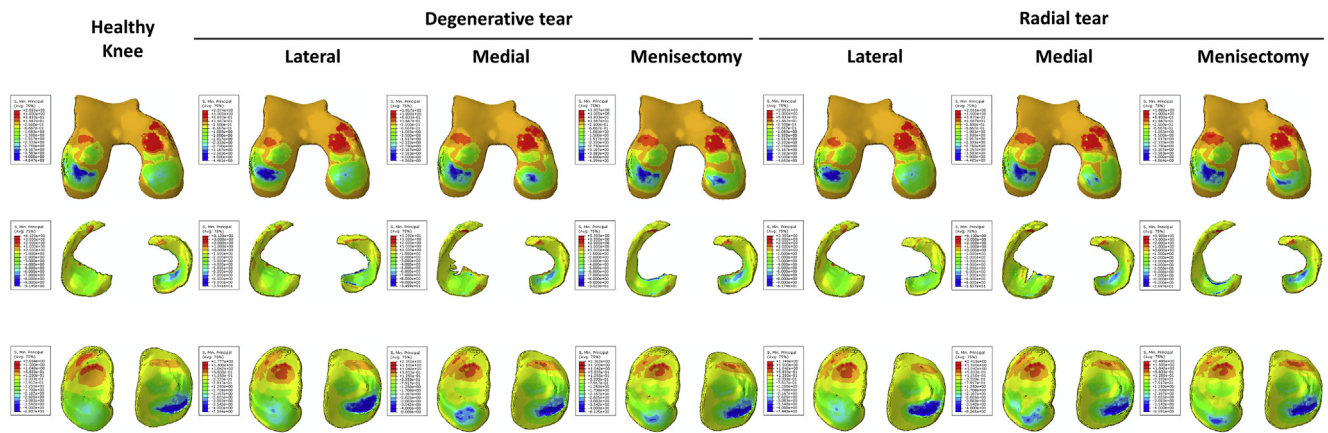


Figure 7 The results of compressive stress on the femoral cartilage, menisci and tibial cartilage under slight flexion simulation. Healthy knee and different types of tears were shown from left to right as the captions indicated.

Table 7 Meniscus extrusion (mm) under slight flexion simulation.

Injury	Healthy knee	Degenerative tear			Radial tear		
		Lateral	Medial	Meniscectomy	Lateral	Medial	Meniscectomy
Medial	3.16	3.27	3.59	3.77	3.26	3.77	3.96
Lateral	3.33	3.40	3.39	3.42	3.46	3.41	3.50

displacement of the medial meniscus than the degenerative tear and was similar to the results for static stance simulation.

Discussion

The most significant finding of the present study was that degenerative and radial tears could cause diverse changes on the load distribution of the knee. Damage to the medial meniscus results in increased load on the cartilages and menisci compared with the lateral meniscus, and the resultant meniscectomy of the medial meniscus induced significantly more stress on the knee components and suggests the unfavourable consequences of meniscectomy.

In this study, a detailed FE model of the knee joint with bones, cartilages, menisci and main ligaments was constructed to assess the biomechanical changes to the knee joint after degenerative or radial tears to the menisci. The magnitudes of compression and shear stresses of the intact knee under static stance simulation were similar to those of previous studies (Table 8) [11,13]. This demonstrates that

our FE model was reliable to demonstrate biomechanical changes to the knee joint.

Degenerative tears of the menisci usually occur in patients older than 40 years. This is the age when symptoms of osteoarthritis, pain, swelling and locking of the knee start to appear [20]. Our results illustrated a detailed compressive and shear stress on the cartilages and menisci after degenerative meniscal tears. This explains why the menisci become more fragile and tear easily after degenerative tears, as more stress concentrates on the edges of tears and compromises the matrix. In addition, increased stress on the cartilages of both femoral condyle and tibial plateau also results in the early proteolytic degradation of the meniscal matrix and the articular cartilage, which then decreases tensile strength, contributing to the progression of osteoarthritis [21].

It has been reported that radial meniscal tears of up to 60% has no effect on the magnitude or location of peak contact pressure across the tibial plateau, whereas 90% of the tears led to a slight increase in peak pressure magnitude and a posterior shift in the location of the force transmission [22]. This contradicts with our results that

Table 8 Comparison of the stress with published studies for the intact knee joint.

Studies	SSFC (MPa)	SSM (MPa)	SSTC (MPa)	CSFC (MPa)	CSM (MPa)	CSTC (MPa)
Our model	2.00	6.72	2.40	4.25	9.15	6.81
Shriram D et al.	1.93	—	2.32	2.76	—	3.52
E.Peña et al.	—	—	—	3.11	3.82	2.19

CSFC = maximum compressive stress on femoral cartilages; CSM = maximum compressive stress on meniscus; CSTC = maximum compressive stress on tibial cartilages; SSFC = maximum shear stress on femoral cartilages; SSM = maximum shear stress on meniscus; SSTC = maximum shear stress on tibial cartilages.

radial tears have similar load changes with degenerative tears. This discrepancy could be attributed to the range of tears. The tears in their study almost extended to the periphery, resulting in the loss of hoop tension, whereas tears in our study only reached the middle third of the meniscus, which was the same range as for degenerative tears, resulting in similar change to shear and compressive stress.

Degenerative and radial tears may not be considered to be repairable and can impair the function of the meniscus, leading to increased wear and degenerative changes to the affected joint [23]. Thus, meniscectomy is usually performed to treat such tears to relieve the symptoms of knee pain caused by the damaged menisci. The results of load distribution in our study showed additional changes when tears occurred at the medial meniscus compared with lateral tears. These results are in concordance with previous studies, which found that the medial meniscus is more important than the lateral meniscus to restrain uniplanar

anterior loads on the tibia [24]. Moreover, compared with the medial meniscectomy, the results of lateral partial meniscectomy showed less biomechanical changes, which was the reason why we took the medial meniscectomy into consideration mainly (Figure 8). The results of maximum compressive and shear stresses showed increased mechanical stress on the cartilages and menisci after meniscectomy, which was in agreement with the study conducted by Dong et al. [6]. They also performed resultant partial meniscectomy after meniscal tears and found a positive impact for the maintenance of high levels of contact stress. This could be due to the extrusion of the menisci. As is shown in Figure 9, when vertical and anterior loads are applied to the knee joint, the intact menisci had a slight extrusion and displacement to provide adequate contact area between the cartilages of the femoral condyle and tibial plateau. This perfectly absorbs the load from the femur to the tibia. However, increased meniscal extrusion

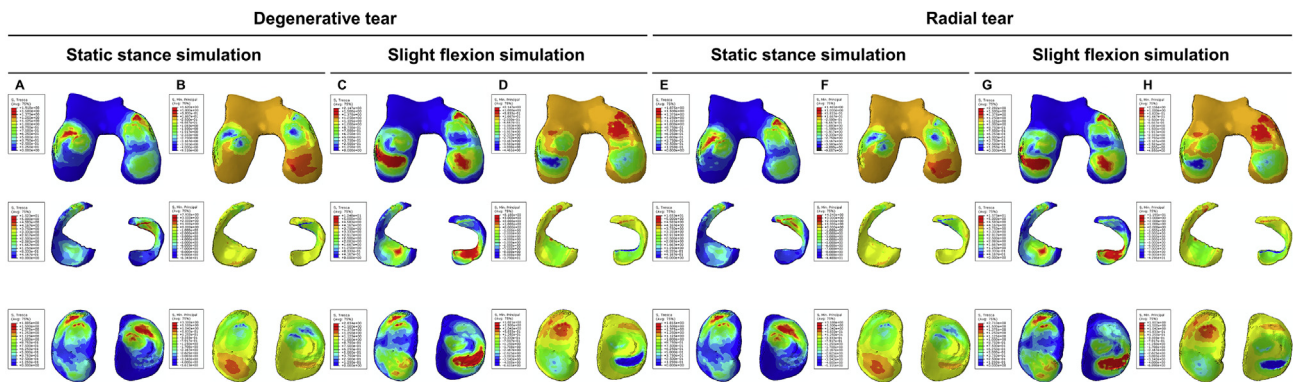


Figure 8 The results of shear and compressive stress on the femoral cartilage, menisci and tibial cartilage under static stance and slight flexion simulation. Different types of tears were shown from the left to right as the captions indicated. (A), (C), (E), (G) The shear stress; (B), (D), (F), (H) the compressive stress.

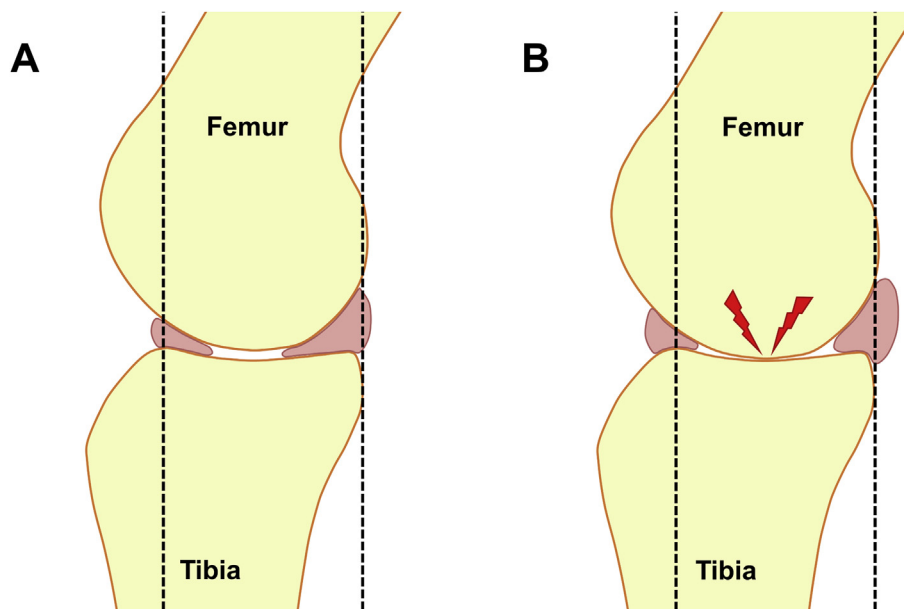


Figure 9 Schematic illustrations of the medial meniscus under slight flexion simulation. (A) The healthy knee; (B) the meniscectomy knee. Dashed lines denote the anterior and posterior margins of tibial plateau.

and displacement were observed in our study after medial meniscus meniscectomy and was larger than that of isolate degenerative or radial tears. This suggests an increase in direct contact area between the cartilages of the femoral condyle and tibial plateau. Without this shock absorption function of the menisci, early degeneration of the cartilages and early onset of osteoarthritis occurs.

The present study has some limitations. First, menisci and cartilages were assigned with idealized linearly elastic material models, whereas nonlinear models would approximate better the behaviour of these structures. However, studies have shown that linearly elastic material properties are able to stimulate bulk behaviour of cartilage accurately [25]. Second, soft tissues including capsule and other small ligaments were not included into the model, which may also provide restriction to the extrusion of the meniscus. Third, two types of simulation without large flexion of the knee were applied in our study. It would be more significant to reveal the stress distribution with different flexion angles of joint. Further research with more complicated material models is needed to investigate the influence of meniscal tear and meniscectomy on the knee biomechanics.

Conclusion

In this study, a realistic 3D knee FE model containing bones, cartilages, menisci and main ligaments was constructed and used to investigate the effects of degenerative and radial meniscal tears and resultant meniscectomy on the stress distribution of the knee under both static stance and slight flexion simulations. Our results demonstrated that the compressive and shear stresses were increased in meniscal tears and increased significantly when meniscectomy was performed. Increased meniscus extrusion may explain the mechanism for higher stress on the components of the knee. The results of our study may guide surgeons to preserve more of the meniscus when performing meniscectomy.

Conflicts of interest statement

All authors declare that they have no conflict of interest.

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Author contribution

K.Z., L.L. and Q.J. contributed in conception and design of study and revised the manuscript critically for important intellectual content. K.Z., L.L. and X.Y. contributed in data acquisition. K.Z. and L.L. analyzed and interpreted the data and drafted the manuscript. All the authors approved the final version of the manuscript to be published.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jot.2018.12.004>.

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