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# Numerical simulation and related experimental research of the mechanical behavior of knee joint

Chunqiu Zhang*, Qiuyue Zhang, Jinduo Ye, LIlan Gao, Xuemei Ma
Tianjin Key Laboratory of the Design and Intelligent Control of the Advanced Mechatronical System School of Mechanical Engineering, Tianjin University of Technology, Tianjin, (P.R.CHINA)
Binshuixi Road No 391, Xiqing District, Tianjin 300384, (CHINA)
E-mail: zhang_chunqiu@126.com

## ABSTRACT

Objective: to reduce injury under physiology load and provide guidance to knee joint recovery by research mechanical behavior of knee joint under physiology load. Methods: A 3D finite element model was established considering total knee joint with meniscus, cartilage and ligament, and numerical simulation was carried out under the condition of standing on two legs and one leg respectively by using CT scan images and 3d reconstruction software. Electrical logging experiment was carried out on artificial knee joint, and computing result and experimental result were contrasted. Results: Comparison between numerical simulation with artificial knee joint and experiment demonstrates calculation model established in this paper reflects mechanical behavior of knee joint under physiology load correctly. The load applied to knee joint when standing on one leg is greater than that of standing on two legs. The load of inner side of both knee joint cartilage and meniscus are relative large and they are easy to be worn. Contact stress of the inner edge of meniscus is relative large, leading the inner edge tend to be worn. Among contact stress, numerical order from large to small is meniscus, tibial cartilage and femur cartilage. When meniscus is injured, load transports mainly through articular cartilage. Conclusions: The results of numerical calculation and electrical logging experiment show total knee joint model with meniscus, articular cartilage and ligament can reflect mechanical behavior of knee joint under physiology load correctly. Meniscus plays an important role in bearing load within knee joint. Protecting meniscus from being injured is important to protect knee joint. There are significant meanings in protecting knee joint, and designing and optimizing biology instrument and prosthesis.

## KEYWORDS

Total knee joint model; Numerical simulation; Experiment; Meniscus.

## INTRODUCTION

Human knee joint includes femur, tibia, patella, meniscus, ligaments, cartilage and other soft tissue, whose functions are transferring load, taking part in sports, assisting conservation of momentum and providing couple for the movement of the legs. Due to complex structures and comprehensive functions, human knee joint is prone to an elevated risk of injures. Osteoarthritis (OA) is a chronic degenerative disease, whose morbidity increases with the age. It has been showed that 50% of the people over the age of 50 and 90% female and 80% male of over the age of 65 were suffering from the disease[1]. Therefore, it is extremely important to research the biomechanical properties and behavior of human knee joint. Staining method and pressure-sensitive sheet method are used to analyze the biomechanics of knee joint in currently work, but they are also restricted due to high cost, large difference in vitro and in vivo conditions and uncontrollable situations. Although in numerical simulation, 2D models and static models are used to simulate and analyze human knee joint, most of these models are inconsistent with the reality. Brekelmans et al[2] applied finite element method to the study of vertebrate biomechanical. Currently, finite element method has become an important way to acquaint the mechanical behavior of human body deeply[3]. With the improvement and constant updating of image capture software and image processing software, finite element technology has been widely used in biomechanical studies of knee joint[4].

Finite element model of knee joint has been built by MRI or CT technology collecting data. In 2007, Zhangyu, Hao Zhixiu et al[5] established 3D finite element model of human knee joint by MRI image data, which included tibia plateau, femur end, articular cartilage and meniscus, except ligaments. Jiang Hualiang et al[6] established 3D finite element model of human knee joint that included bone, cartilage, meniscus and main ligaments by MRI and reverse engineering software. They verified the validity of the model, but did not analyze it deeply. At present, most of the finite element models of human knee joint just consider femur and tibia, but it is not complete for there are not meniscus and ligaments. This paper established a total knee joint finite element model including femur, tibia, patella, articular cartilage, meniscus and ligaments by Mimics and Geomagic Studio. Considering the nonlinear contact between articular cartilage and meniscus, the condition of standing on one leg and two legs were simulated and analyzed respectively by ABAQUS. It has been showed that meniscus played an important role in bearing weight, and it had relative high stress. Meniscus damage will change the way of the load bearing of human knee joint and aggravate the burden of articular cartilage, even cause the damage of human knee joint.

## MATERIALS AND METHODS

### Establishing total knee joint model

Select a normal male volunteer, no history of knee injury, X-ray examining to exclude damage, pathological changes, and so on. Spiral CT scanning was carried out on the knee of volunteer, slice thickness was 0.8mm, and scanning layer was 1449, to get the images of continuous cross section and sagittal plane. Scanning data was saved and output in DICOM format. Before the experiment, volunteer was informed related content and consented. Medical CT scanning data source were introduced into Mimics10.01 (interactive medical imaging control system of Materialize Company, Belgium) to obtain graphs of cross-sectional, coronal and sagittal plane. Gray value was set and threshold analysis was carried out. Besides, the part planning to reconstruct was selected by using software threshold. Software shows different structure planning to reconstruct in different colors with MASK. Different structures are modified through editing and regional growth function. And then 3D model of knee joint was obtained through skin reconstructing by 3D calculation function. The model was saved and exported as STL format. The file in STL format obtained by Mimics was imported into reverse engineering software of Geomagic Studio, and triangular facet data was denoised, smoothed and removed the artifacts. Through establishing outlines, smooth, regular and large patches were generated. Finally, the model was formed fitting surface by fitting surface tools, and outputted in IGES format. Through Pro/Engineer software transforming 3D model format into. X-T format, 3D solid model of total knee joint was acquired. Finally, the 3D solid model was imported into finite element analysis software ABAQUS, setting element types and material properties, and meshing. 3D finite element model of knee joint was ultimately obtained.

Cartilage and meniscus plays a role of buffer load and impact in knee joint. As structure between cartilage and bone in 3D reconstruction cannot ensure good contact, Boolean operations were carried out in ABAQUS to make it. For ligaments playing a role of ensuring the stability of knee joint, cartilage and ligaments were taken into account in knee joint model to reflect the mechanical behavior of knee joint better.

Most biological materials are non-uniformity and anisotropy, simulation and the calculation are very complex. A number of studies have confirmed that when conducting small deformation analysis, it can be simplified as continuous, homogeneous, isotropic and linear elastic material. Donzelli et al[7]thought there was no prominent changes in a short time after bearing elastic whether it was material or loadviscous-elastic material. Therefore, bones, cartilages, menisci and ligaments were deemed as linear elastic material in the model. Unit types and material properties of each component in knee joint model are shown in TABLE 1[8,9].

### Contact conditions and boundary conditions of total knee joint

Femur and femoral cartilage, tibia and tibial cartilage were set as binding contacts in the model. Femur cartilage, tibial cartilage, and meniscus connection was set as contact, and front and rear foot of meniscus were fixed in the tibial plateau. Binding constraints were carried out in ligament and the corresponding attachment points. Ligament comprises front (rear) cruciate ligament, patellar ligament, medial collateral ligament, and lateral collateral ligament. The boundary conditions of finite element model were follows: the displacement of the three axis directions of ankle was restrained, any constraint was not taken near the knee joint, and joints were restrained entirely depending on ligament, which ensured degrees of freedom in coronal and sagittal plane, and cross section. Boundary condition of load was applied concentrated loads in the femoral head. This paper considered two kinds of load: single leg stand and two legs stand. When standing on one leg, the femoral head undertook 62% of the weight from the upper part of the body[10]. When standing on two legs, femoral head undertook 202N, while standing on one leg, femoral head undertook 403N.

**TABLE 1 : Element type and material parameters of each component**

| Structure | Element Type | Elasticity modulus/MPa | Poisson ratio |
|---|---|---|---|
| Skeleton | body element | 12000 | 0.30 |
| AC | body element | 5 | 0.46 |
| Meniscus | body element | 59 | 0.49 |
| PL | body element | 225 | 0.3 |
| MCL/LCL | body element | 60 | 0.3 |
| ACL/PCL | body element | 200 | 0.3 |

Computational model includes 17,864 bone structure units, 88,691 cartilage units, 4485 meniscus units and 34,033 ligament units. Total knee finite element model including femur, tibia, fibula, patella, cartilage, menisci and ligaments is shown in Figure 1.

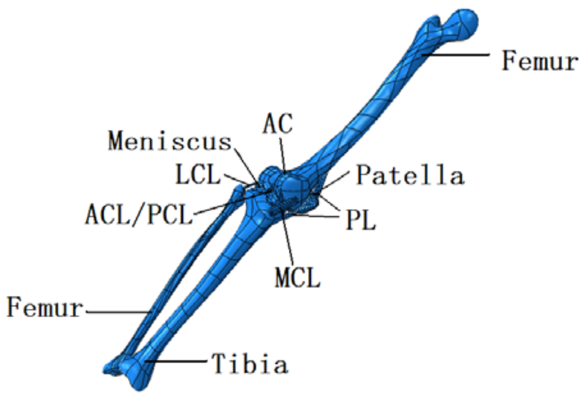



**Figure 1 : The knee joint model of containsing the cartilage, meniscus and ligament**

## RESULTS

### Stress results and analysis of knee joint when standing on one leg

Figure 2 depicts the overall stress distribution map of knee joint when standing on one leg. Figure 3 plots the contact stress distribution map of the femur knee cartilage, tibial cartilage and meniscus.

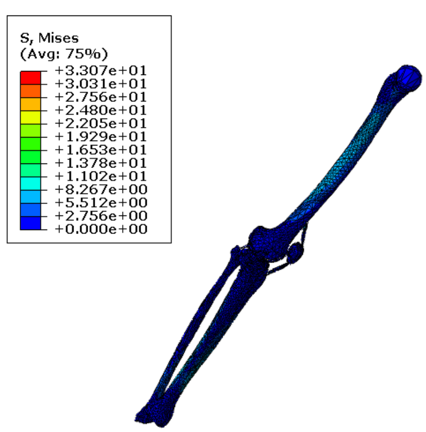
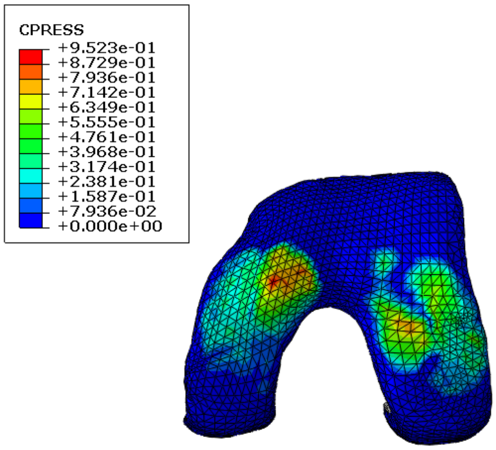
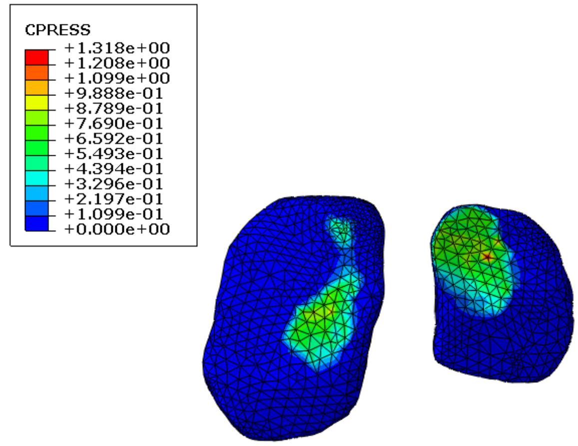


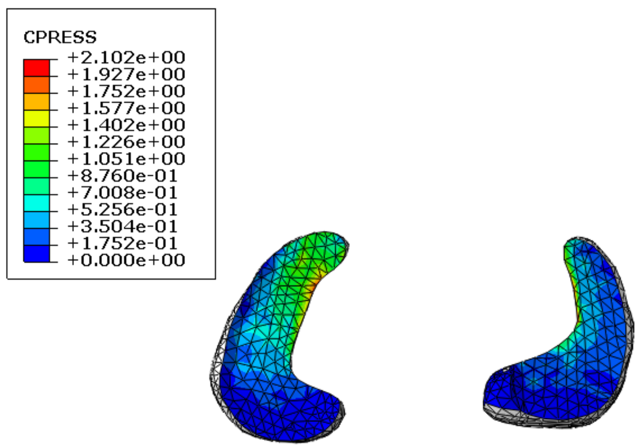

**Figure 2 : Overall stress distribution map of knee joint when standing on one leg**




**a. Contact stress distribution map of the femur knee cartilage**




**b. Contact stress distribution map of the tibial cartilage**




**c. Contact stress distribution map of the meniscus**

**Figure 3 : Contact stress distribution map of the femur knee cartilage, tibial cartilage and meniscus**

It can be seen from the figure, the maximum contact stress of femur cartilage is about 0.952MPa, locating in the inner side of femur cartilage, that of tibial cartilage is 1.318MPa, locating in the medial edge of tibial cartilage, and that of meniscus is about to 2.102MPa, locating in the inner edge of the medial meniscus. The inner edge of the meniscus is thin, while its outer edge is thick, besides, loads on inner edge is greater than that of outer edge, which makes the inner edge of the meniscus is easy to wear.

**The comparison of contact stress between standing on one leg and two legs**

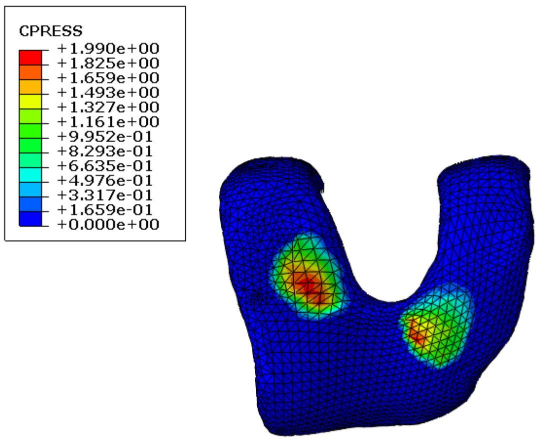
**TABLE 2 : Contact stress comparison of cartilage, meniscus while standing by single leg and legs**

| Structure | Standing on two legs /MPa | Standing on one leg /MPa | Increased percentage (%) |
|---|---|---|---|
| Femur cartilage | 0.5986 | 0.9523 | 59.09 |
| Tibial cartilage | 0.9010 | 1.318 | 46.28 |
| meniscus | 1.276 | 2.102 | 64.73 |

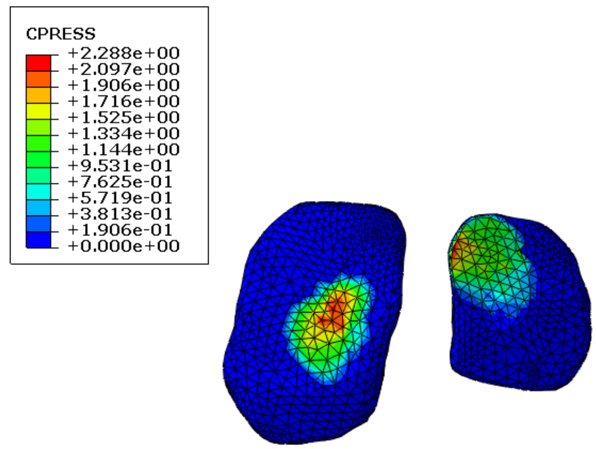
It can be seen from the TABLE, with the increment of the load, the contact stress of the femur cartilage, tibial cartilage and meniscus increases when changing from standing on one leg to two legs. In both cases, contact stress of the meniscus is the largest, that of femur cartilage is the smallest, and that of tibial cartilage is between of them. It can be seen from the data of increased percentage, the growth rate of meniscus is the largest and that of tibial cartilage is smallest. Therefore, the meniscus plays an important role in the load transport in knee joint.

**Effect of meniscus on knee joint bearing capacity**

It can be seen from the figure4, the maximum contact stress of femur cartilage is about 1.99 MPa, that of tibial cartilage is 2.288 MPa without meniscus in knee joint. Contact stress of tibial and femoral cartilage is greater than that in the model with meniscus. Contact stress distribution is relatively concentrated and the rest of the parts does not produce stress, the stress on the location of the cartilage wear and tear. The location of the cartilage wear is the position of stress concentration.




**(a)Contact stress cloud of femoral cartilage**




**(b)Contact stress cloud of tibial cartilage**

**Figure 4 : Standing on one leg, contact stress cloud of femoral cartilage and tibial cartilage without meniscus (MPa)**

**TABLE 3 : Contrast of the contact stress of Standing on one leg (not) to consider joint ligament**

| G | Contact stress of GR /MPa | Position | Contact stress of JR /MPa | Position | Contact stress of BYB /MPa | Position |
|---|---|---|---|---|---|---|
| No ligament model | 1.474 | Inner | 1.413 | Inner | 2.102 | Inner |
| Ligament model | 0.952 | Inner | 1.318 | Inner | 2.006 | Inner |

**Note: GR: femoral cartilage. JR: tibial cartilage. BYB: meniscus**

In the normal joints, loads transport both by meniscal and cartilage, whereas they mainly transport by articular cartilage when meniscus is worn, which enlarges the risk of the wear of articular cartilage. The wear of knee joint meniscus will lead to the internal load transfer change, resulting in an uneven stress distribution and deterioration of joint disease.

**Effect of ligaments on knee joint bearing capacity**

It can be seen from the TABLE3,contact stress of tibial and femoral cartilage is greater than that in the model with ligaments. Using the boundary conditions, degree of freedom of transverse and coronal plane in the model is limited, the whole model is stiffness and the stress value is larger. It is found that the results by the model considering ligament agree with the animated knee since the model considering ligament guarantees the degree of freedom in coronal plane, vertical plane and transverse section.

**Experimental verification of numerical simulation**

In order to verify the results of numerical calculation, artificial model of femur, tibia, fibula and patella were manufactured and electromotive tests on knee joint were conducted. The measure points distribution refers to the results of numerical calculation, as shown in TABLE 3. Experimental apparatus includes electronic universal testing machine (WDW-10) and static strain testing system (DH3818), as shown in Figure 4. In this study, tibia and fibula were fixed by gypsum, load was applied on femoral head and magnitude of load was controlled by testing machine. Numerical simulation of electronic test result was conducted on knee joint model made by high polymer material, whose parameters were gained from tests on high polymer material. The elasticity modulus and Poisson ratio of artificial bone were 370 MPa and 0.49, respectively. Articular cartilage and meniscus were not taken into account.

**Figure 5 : Experiment test site**

In order to compare the results of numerical calculation and experiment, coordinate and direction cosine of measure points were measured under given coordinate system considering the random direction of strain gages on measure points. Meanwhile, the strains of the measure points in numerical calculation were extracted as the same position with the experimental measure point and the strains of strain gages on measure points were calculated. The formula is shown as follow:

$$\varepsilon_{\mathrm{r}} = \varepsilon_{\mathrm{x}} l_x^2 + \varepsilon_{\mathrm{y}} l_y^2 + \varepsilon_{\mathrm{z}} l_z^2 + \gamma_{xy} l_x l_y + \gamma_{yz} l_y l_z + \gamma_{zx} l_z l_x \tag{1}$$

Where $\varepsilon_{\mathrm{r}}$ is the strain in one point of any direction, $\varepsilon_{\mathrm{x}}$ , $\varepsilon_y$ , $\varepsilon_z$ , $\gamma_{xy}$ , $\gamma_{zx}$ and $\gamma_{yz}$ are the strains of the points in numerical calculation, $l_{\mathrm{x}}$ , $l_y$ and $l_z$ are the direction cosines of one point.

The simulation results in the direction of strain gages were calculated and compared with the results of experiment result later. The comparison is shown in TABLE 3. It can be found that the relative error of five measure points is under 10% among the nine measure points, while the other four are opposite. The smallest error between numerical calculation and experiment is -4.9% that occurs near the lesser trochanter, while the largest error is -22.91% that occurs in back of tibial plateau. It demonstrates a good agreement between numerical calculation and experiment from TABLE 3, which means that the model and the method of numerical calculation are close with the reality and can reflect the mechanical properties of total knee joint.

**TABLE 4 : The comparison between numerical simulation and experiment result of knee joint**

| **Name of paster location** | **x** | **y** | **z** | **l** | **m** | **n** | $\varepsilon_{\mathrm{r}}$ **in simulation** | $\varepsilon_{\mathrm{r}}$ **in experiment** | **Error (%)** |
|---|---|---|---|---|---|---|---|---|---|
| Near lesser trochanter | 30.45 | 254.16 | 131.81 | 0.0336 | 0.0987 | 0.995 | -6784.93 | -7136 | -4.9 |
| Lateral condyle of femur | 314.71 | 304.36 | -146.03 | 0.0484 | 0.0637 | 0.997 | -189.28 | -174 | 8.78 |
| Medial malleolus of femur | 254.65 | 296.19 | -150.87 | 0.0337 | -0.0295 | 0.998 | -196.94 | -184 | 6.52 |
| Front of condyles of femur | 312.78 | 241.45 | -117.88 | 0.0068 | -0.0461 | 0.999 | 444.04 | 420 | 5.71 |
| Back of condyles of femur | 300.16 | 272.05 | -107.78 | 0.0213 | -0.213 | 0.977 | -1219.73 | -1103 | 16.86 |
| Inner side of tibial plateau | 255.39 | 269.53 | -196,6 | -0.156 | 0.0037 | 0.988 | -182.25 | -221 | -17.53 |
| Outer side of tibial plateau | 359.7 | 284.74 | -197.25 | 0.138 | 0.165 | 0.976 | -693.09 | -636 | 8.98 |
| Back of tibial plateau | 303.48 | 281.5 | -225.32 | -0.78 | 0.225 | 0.971 | -522.77 | -473 | -22.91 |
| Front of tibial plateau | 312.47 | 239.54 | -238.3 | -0.33 | -0.0082 | 0.94 | -231.86 | -191 | 10.21 |

**Note: X, Y, Z is the patch position in electric logging test,lx,ly,lz is the direction cosine**

## CONCLUSIONS AND DISCUSSIONS

The stress of inner side of femoral cartilage, tibia cartilage and meniscus of knee joint was relative large, and the inner edge of the meniscus was suffered by relative large contact stress and easy to wear, which are consistent with clinical statistics. Among contact stress, numerical order from large to small was meniscus, tibial cartilage and femur cartilage. The load applied to knee joint when standing on one leg is greater than that of standing on two legs. Generally knee joint load mainly transported by meniscus. But when the load increased or meniscus injured, the contact area between femur cartilage and tibial cartilage increases, and the load would be transported by articular cartilage at that time. Seedhor et al[11] found that the stress on tibial joint whose meniscus was cut off was three times compared with the one with whole meniscus when he was loading via corpse experiments. Shang Ping and Xu Yongtao et al[12] analyzed 85 meniscus injury cases through the arthroscope and discovered that meniscus injury can cause cartilage injury. The wear of knee joint meniscus will lead to the internal load transfer change, resulting in an uneven stress distribution and deterioration of joint disease.

Comparison between numerical simulation with artificial knee joint and experiment demonstrated the validity and applicability of numerical simulation, thereby demonstrated the validity of method establishing knee joint and the applicability of establishing human knee joint in this paper. Mechanical behavior of knee joint could be researched by numerical simulation method.

Data information of knee joint was acquired by CT scanning technology, whose sectional morphological structure was total, and three-dimensional was accurate. And relative position of each component of knee joint was determined. Total knee joint model was established, proper constitutive model was selected to sclerotin structure and soft tissue, and corresponding material parameter was defined. Ligament in the model was defined as solid element rather than spring element in previous models, which made the model conform to the reality better. The comparison and analysis with previous models testified the validity of this model. The top of femur was loaded analyzing and researching the distribution of stress in contact area. Comparing with femur and tibia cut off and defining them as rigid body in previous work, establishing total femur and tibia and loading on the top of femur conform to human lines of force better. And that sclerotin structure was regarded as elastomer conforms to the reality better. Boundary constraint condition in the model was formulated according to model conditions and relevant literature[13], which possesses preferable boundary constraint similitude. There are significant meanings in preventing and treating joint disease, reducing injury of joint, and designing and optimizing of biology instrument and prosthesis.

## CONFLICT OF INTEREST

This article content has no conflict of interest

## ACKNOWLEDGEMENT

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