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# Biomechanical optimization of the correction angle during high tibial osteotomy using finite element analysis

**The Graduate School of the University of Ulsan**

**Department of Mechanical Engineering**

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# Biomechanical optimization of the correction angle during high tibial osteotomy using finite element analysis

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**By**

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# ABSTRACT

Knee osteoarthritis (OA) is one of the most common chronic diseases of the tibiofemoral joint and one of the leading causes of disability in middle and older ages. High tibial osteotomy (HTO) corrects the lower limb's hip knee angle (HKA), thereby rebalancing the load on the lateral and medial compartments to treat varus deformity. However, while correcting the lower limb HKA, overcorrection and undercorrection often occur. This study uses computer simulations to investigate the effects of overcorrection and undercorrection during HTO surgery. Finite element knee models were established with HTO and three types of undercorrection (three models), neutral position (one model), and overcorrection (three models) based on correction angles. Static structural analysis was carried out using ABAQUS to compare von Mises stress distribution and lateral and medial compartments stress. The results of this study, upon correcting the HKA to the neutral position, the medial compartment stress decreased, and the medial compartment stress slightly increased. Furthermore, correcting the HKA to overcorrection or undercorrection further reduced medial stresses. Furthermore, 2° valgus correction produced the least medial compartment stress and more balanced stress in the medial and lateral compartments. Therefore, minimum undercorrection or overcorrection can optimize the surgical effect of HTO.

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# FIGURE LIST

# Chapter 1 Introduction

Knee osteoarthritis (OA) is one of the most common chronic diseases of the tibiofemoral joint and one of the leading causes of middle-aged and older people's disabilities. [1] It is recognized that the etiology of OA is multifactorial and complicated, such as age, obesity, joint soft tissue injury, arthrosis, congenital abnormality, and malformation. High tibial osteotomy (HTO) is commonly used for active young patients with medial compartment knee OA. [2] Many patients can return to work, and most resume their sporting activities after HTO.[3] HTO reduces the stress on the medial knee compartment, thereby relieve knee joint pain by shifting the weight-bearing axis (WBA) from the lateral side to the medial side. [4] Alignment of hip knee angle (HKA) is one of the most critical factors affecting HTO surgery.

Even though HTO surgery is already very prevalent, the optimal re-alignment of the HKA still has many uncertainties. [5] A 10 to 13-year follow-up study found that overcorrection and under-correction are important reasons that affect HTO surgery. [6] Despite precise pre-operative planning and careful surgery, overcorrection and under-correction often occur. These alignment correction errors may be due to soft tissue laxity caused by varus or valgus. [7] However, over-correction is used to treat varus and valgus patients caused by knee osteoarthritis and may have better surgical results. [8,9] Historically, some doctors have aimed to adjust to three to six degrees of eversion after surgery. However, it has recently been improved because the correction angle may cause soft tissue damage. Correcting a suitable angle after HTO surgery and understanding the relationship between over-correction and under-correction and the resulting stress redistribution will help future surgical technology development. [10,11]

OA is generally caused by degenerative knee joint lesions, trauma, strain, and other reasons. According to the location of the lesion, it can be divided into deformity within the knee joint and external deformity of the knee joint. Among them, the medial compartment of the knee joint arthritis is the most common, and the treatments include TKA surgery, UKA, and HTO surgery. HTO surgery has been widely used in middle-aged to moderate knee arthritis in recent years and has achieved good clinical results. Because HTO surgery is simple, low cost, and has sound clinical effects, it is almost defaulted to be the medial compartment knee arthritis protection. The HTO surgery is the only surgical method for knee treatment and its purpose is to adjust the lower limbs' force by changing the lower limbs' HKA angle. However, the alignment of the lower limbs during surgery is often the key to the outcome of the surgery. Many biomechanical experiments have also verified the relationship between the HKA angle and the effect of HTO surgery. It is challenging to explore the internal stress of the bones because no sensor is small enough to be inserted into a human body without disturbing response. However, the finite element (FE) method, numerical simulation, can resolve all the limitations and has been used in many studies. [15-18] Therefore, this study aimed to evaluate the impact of overcorrection and undercorrection of lower limbs in biomechanics using validated after-HTO FE knee joint models. However, ordinary experiments are challenging to simulate the structure of the knee joint and cost a lot. With the development of digital technology, finite element analysis mechanics has been widely used in biological sciences. Compared with traditional biomechanics experiments, finite element analysis has better operability. No experimental equipment and other experimental conditions are required. As long as the model is established accurately, the data obtained has high reducibility. These advantages of the finite element can better make up for the shortcomings of traditional biomechanics experiments. For knee joint biomechanics experiments, finite element analysis is an ideal method.

# Chapter 2 Knee injury and treatment

First, this chapter introduces the anatomical structure of the knee joint and introduce the background knowledge of OA. After that, HTO surgery is introduced to treat OA patients. Then, the principle of the TomoFix fixation system in HTO surgery is explained. And then, the surgical medial open wedge-shaped high tibial osteotomy was described. Next, we will explore the impact of the HKA correction angle on the soft tissues of the lower limbs during HTO surgery. Finally, we will review the application of finite element analysis in biomechanics. By comparing traditional biomechanics experiments and finite element simulations, it will be decided to use finite element simulation stress analysis to verify the improvement of the force of the lower limbs by HTO surgery. The usefulness of the finite element method and its applicability to biomechanics will be discussed.

## 2.1 Knee joint anatomical structure

The knee joint is one of the largest and most complex joints in the human body and the largest weight-bearing joint (under normal circumstances, it can bear 35 kg). It is a pulley joint. The knee joint absorbs part of the force of running and walking. Knee joint the structure is stable and flexible. The knee joint is mainly composed of the femur, tibia, fibula, and patella. The surfaces that touch each other form a joint. The four main ligaments play a fixed role in the knee joint. The four main ligaments are anterior cruciate ligament (ACL), …. In addition, the meniscus on both sides of the joint plays a role in cushioning, shock absorption, and stability. The overall composition is shown in Figure 1. Because the knee joint is heavy and moves more, it is the most vulnerable to injury. Therefore, it is essential to keep the knee joint healthy and maintain its stability and functionality. The quadriceps on the front of the thigh and the posterior muscle group on the back are two major muscle groups that play a vital role.

From childhood to adult, there are many uses of knee joint surfaces. The knee joint surfaces are used for walking, squatting, and standing up. The patella articular surface itself is an articular surface that is relatively easy to damage. The distal femur and the proximal tibia are protected by femoral cartilage and tibial cartilage on the knee joint surface. The thickness of the cartilage is about 2-5mm. There are medial and lateral menisci on the articular surface of the tibia with thick edges and tightly connected to the joint capsule. The center part is thinner. The structure of the knee joint surface is shown in Figure 2.

A complete lower limb model is composed of femur, tibia, fibula, femoral cartilage, tibial cartilage, fibular cartilage, meniscus, ACL, PCL MCL, LCL, and each part is interrelated and cooperates to form a complex mechanical structure.

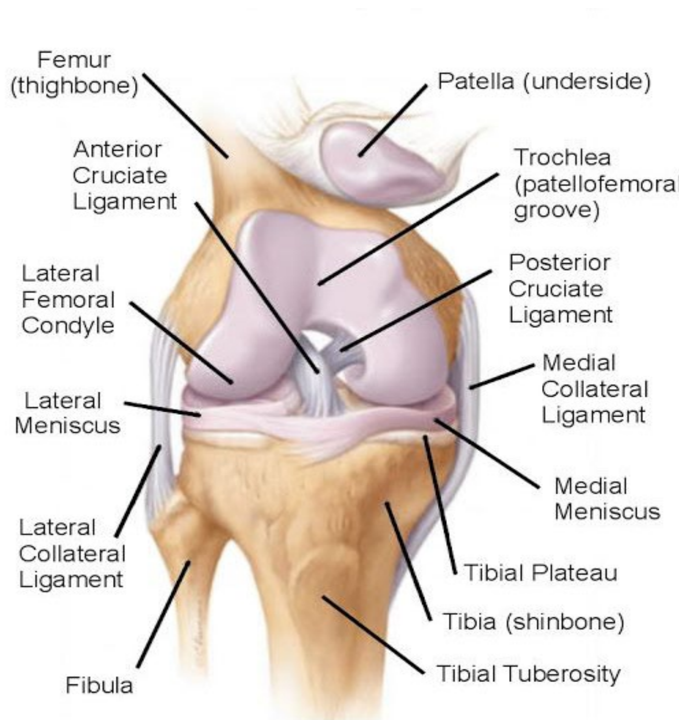



Fig1. Knee joint anatomical structure

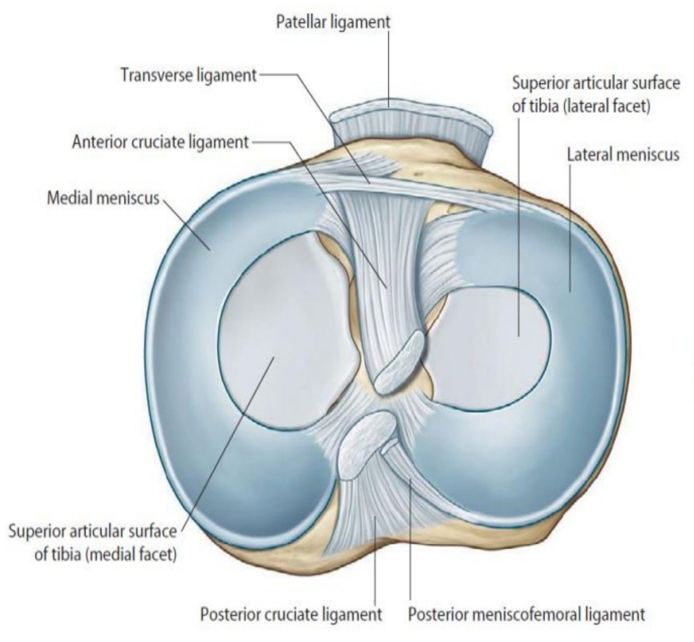



Fig2. Knee joint surface structure

## 2.2 Knee osteoarthritis

Knee osteoarthritis is the most common form of arthritis, affecting millions of people worldwide. However, medial arthritis is more common in a midterm. It grows when the protective cartilage at the end of the bone passes over time. Usually, medial arthritis can be better treated, and for mild patients, it is usually treated by re-adjusting the angle of the lower limbs. This section will introduce the treatment background of varus and valgus and the guidelines for adjusting the angle of the lower limbs.

Symptoms of knee arthritis include pain, swelling, and stiffness. The pain symptoms are usually the most severe in the morning [19]. This is because the knee joint is inactive at night, and the condition will be improved when the knee is reactivated after a short rest. However, the pain will increase again with prolonged activities during the day [20]. These symptoms can affect daily life and people's daily work. When the symptoms are severe, they can affect sleep and require surgical treatment.

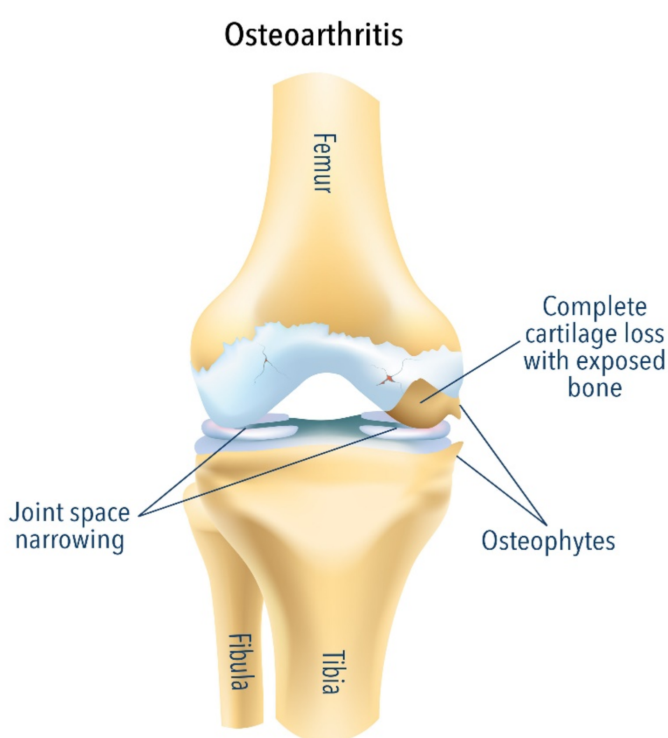


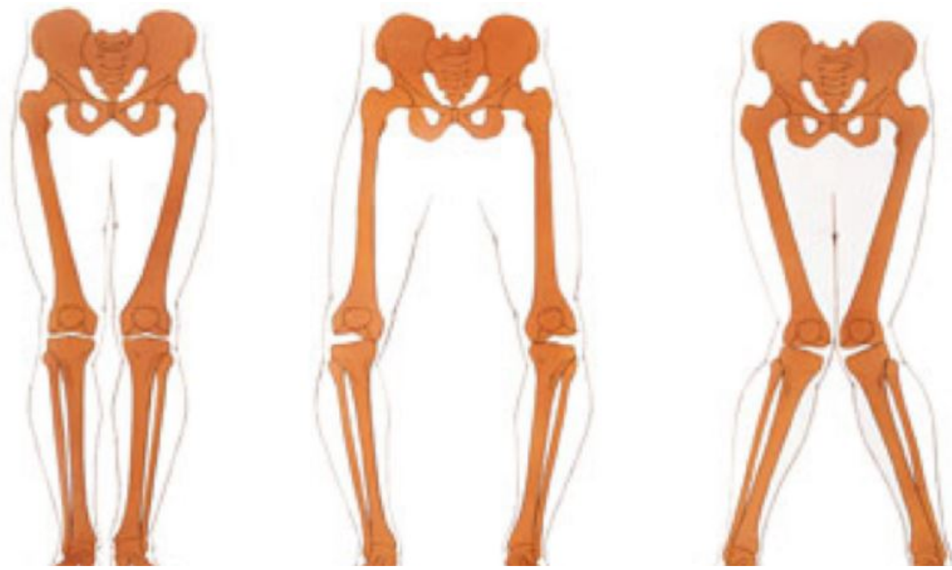

Fig3. Medial compartment osteoarthritis of knee

### 2.2.1 Varus and valgus malalignment

Deformities of the knee joint often cause angulation of the lower limbs (varus or valgus). The causes of pits are healing after fractures, congenital metabolic diseases, congenital malformations, etc... Therefore, the first step of the weight-bearing line is to assess the varus and valgus condition. The HKA angle (hip knee angle) can be used here. HKA angle is the angle between the center of the femoral proximal, the center of the knee joint, and the ankle joint center. The HKA angle of the varus and valgus is plus or minus, respectively. The Weight Bearing Line (WBL) is illustrated in Fig.5 (the pink line) [20].

Knee varus and valgus are some of the more common deformities of the lower extremities. Various causes of frontal knee joint angulation can cause knee varus and valgus deformity. Changes in the weight-bearing state and line of force of the patient's lower limbs, and abnormal walking gait, will inevitably lead to an increase in the load on the knee joint, which will lead to the damage of the articular cartilage and cause degenerative changes in the knee joint [21]. Eventually, it will lead to joint stiffness and walking dysfunction, seriously reducing the patient's quality of life. Therefore, the timely diagnosis and treatment of knee varus are of great significance to maintaining the patient's walking function and improving the quality of life. Since patients with knee varus are much more than those with valgus, this article focuses on knee varus.

Older people often lose mobility due to knee varus due to persistent knee varus problems. To avoid the occurrence of such symptoms, it is necessary to carry out treatment and prevention in advance.



a b c

Fig4. Multiple alignments of lower limbs (a) neutral alignment (b) varus deformity

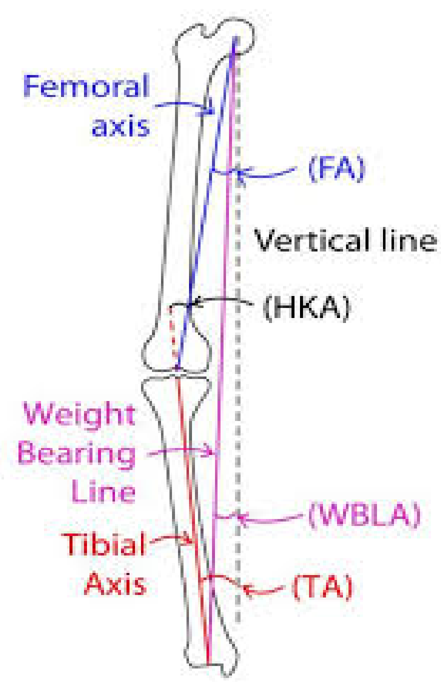



Fig5.Lower limb axial alignment

## 2.3 Medial opening wedge high tibial osteotomy

### 2.3.1 Overview of HTO

High tibial osteotomy is to preserve the knee joint, cut out an osteotomy on the calf tibia, and fix it at one time to reduce knee pressure and reduce the burden of medial cartilage wear. High tibial osteotomy is a general knee-saving surgery in clinics. Clinically used to treat patients with obvious joint deformities, and the high tibial osteotomy is mainly used to replace knee joint replacement surgery [22]. High tibial osteotomy achieves the purpose of adjusting the mechanical environment structure of the knee joint through the osteotomy of the tibia, stretching the joint gap, reducing the wear on the articular cartilage to achieve the purpose of correcting the deformity of the knee joint. Moreover, it alleviates the pain of the knee joint and the limitation of movement. Patients usually need to undergo active functional rehabilitation training after surgery to achieve the purpose of further recovery, which can usually achieve excellent therapeutic effects [23]. High-position osteotomy can only achieve better surgical results by examining the doctor's experience, judging the depth of the incision, judging the angle of the incision, and accurately evaluating it. Recently, with the aid of 3D printing combined with computer tomography, doctors can perform operations more accurately.

High tibial osteotomy is now one of the most commonly used procedures for knee protection treatment, and it has been widely respected in recent years [24]. Because of its good surgical effect and low price, it is widely accepted by patients. even though for some patients with severe knee wear, it also has a good effect. After six months of surgical treatment, it can return to daily life after recovery. In addition, some patients with better recovery can regain their athletic ability.

## 2.3.2 The TomoFix fixation system

Open wedge-shaped high tibial osteotomy (OWHTO) has the advantages of simple technique and operation, slight incision trauma, more accurate deformity correction, and more convenient adjustment of the force line during the operation. In recent years, the introduction of the TomoFix plate and the advancement of surgical techniques have promoted the development of OWHTO. After the operation, patients can bear weight and exercise early, and can resume normal activities well [25]. The incidence of force line correction loss and nonunion is low, and satisfaction has been achieved. The clinical effect that it has been widely promoted in recent years.

For TomoFix plates, titanium alloy structures are often used. Titanium alloy steel plates are titanium alloys used to manufacture medical devices, prostheses, artificial organs, and auxiliary treatment equipment implanted in the human body [26]. They have high specific strength and mechanical properties close to human bones. Better than pure titanium, it also has fatigue resistance, corrosion resistance, and excellent biocompatibility. The immune mechanism of the human body leads to the rejection of any foreign body implanted and kicked, but the degree is different. Titanium alloys are now widely used in transportation, and the technology is relatively matured. Therefore, the degree of rejection is relatively small and relatively controllable. Since it has good strength and toughness, lighter weight, more stable performance, and low rejection, it can be placed in the human body for a long time without taking it out, and it is not affected by re-examination of MRI, CT, and X-rays. Ordinary medical stainless steel internal fixation does not have these advantages.


Fig6. TomoFix plate & screw

Fig7. TomoFix osteotomy system

### 2.3.3 Medial open wedge high tibial osteotomy procedure

Before HTO surgery, the patient should be evaluated as a whole, including the degree of knee joint damage, joint deformity.... Then, after obtaining the patient's full-length X-ray, pay attention to the rotation position of the lower limbs. Then, after analyzing the deformity of the patient's lower limbs, the appropriate hinge position is selected. Moreover, it is necessary to have a proper design of the osteotomy line. Finally, understand the osteotomy angle of the operation.

An excellent surgical plan is a key to a successful operation [26]. First, it will be taking a full-length CT film with a load. Then mark two axes. The mechanical axis is from the center of the femoral head through the center of the ankle joint. The weight-bearing axis passes through the knee joint from the center of the femoral head. (Fig.8). Then determine the osteotomy hinge point, which is generally located at the tibial plateau. The lateral cortex, near the upper end of the tibiofibular joint, is generally located 1.5cm below the articular surface. The position of the distal osteotomy line or the base distance of the wedge-shaped osteotomy depends on the precise calculation before the operation and the observation and measurement during the operation. In important steps, special attention should be paid. Tibial wedge osteotomy can cut off the anterior and posterior cortex first, leaving part of the medial cortex. The osteotomy surface is required to be neat for alignment. The connection between the osteotomy hinge point and the bottom end of the mechanical axis and the load-bearing axis is the correction angle α. Finally, the appropriate steel plate is selected according to the angle and length of the osteotomy opening.

If the patient has more severe osteoarthritis, we will move the force line to the outside in setting the target force line. If the osteoarthritis is not severe and there is no pain, just to correct the deformity, we should put it in a neutral position. For ordinary people, the typical tibial plateau is about 10° backward. Patients with chronic posterior cruciate ligament injury may have knee hyperextension. This symptom can be improved by increasing the tibial plateau posterior during high tibial osteotomy [27]. In contrast, patients with chronic anterior cruciate ligament injury will lack extension of the knee joint, which can be improved by reducing the tibial plateau through high tibial osteotomy.

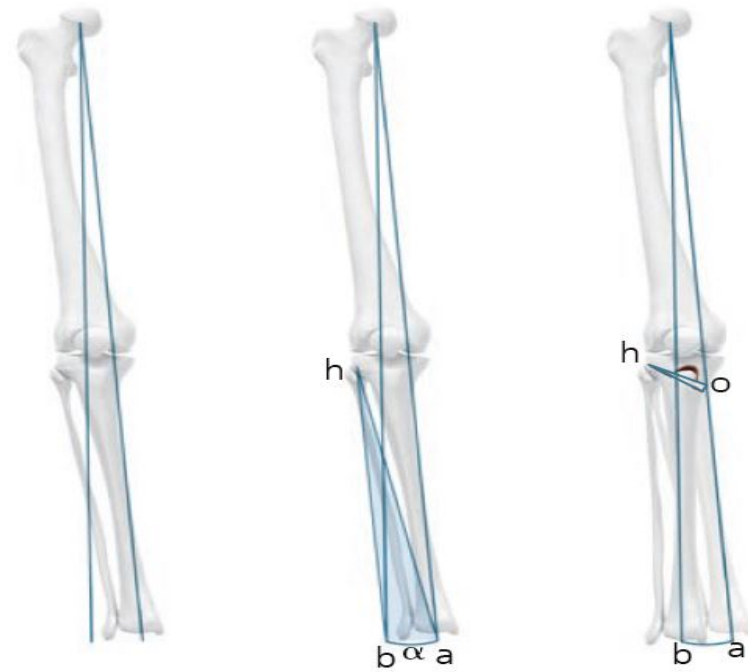



Fig8.Surgical of HTO procedure (right

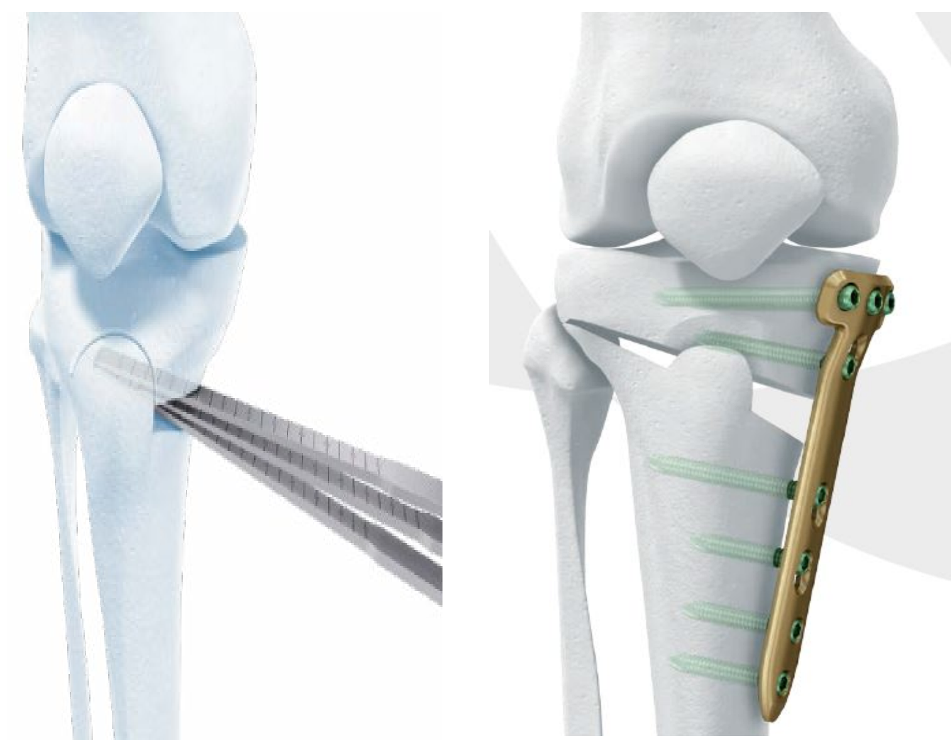


Fig9. High tibia osteotomy

### 2.3.4 Optimization of correction angle

The operating principle of HTO is to transfer the weight line of the lower limbs from the medial compartment to the lateral compartment to reduce the force on the medial compartment. Thus, it improves the balance of forces in the knee joint so that the medial compartment and lateral compartment forces will be rebalanced to reduce pain and improve knee joint function. However, medial arthritis will be worsened if the correction is insufficient, and the weight-bearing line is not moved enough. Furthermore, the opposite lateral compartment will overcorrection. As a result, patellofemoral joint cartilage degenerates, causing pain and other symptoms, leading to early postoperative failure. Therefore, correcting the angle is the key to affecting the effect of HTO surgery [28].

Even if the instruments used in recent surgery are very advanced, doctors usually have a good surgical plan. However, due to the uncertainty of the operation, errors often occur in the correction of the lower limb weight-bearing line [29]. As a result, there will be undercorrection or overcorrection. However, the lack of correction in the past and the lack of biomechanical research have inconvenienced the operation. When the knee ligaments of varus patients are loose, the correction angle is often too large, and overcorrection occurs. The surgery will fail if the angle is too large in the past.

On the contrary, if the correction is insufficient, it will affect the effect of the operation. For example, if the correction angle is too small, the patient's pain will often not be improved well. Therefore, overcorrection and undercorrection significantly affect the results of the operation.

## 2.4 Introduction to finite element analysis in knee joint biomechanical study

The finite element method is essential in computational mechanics. In recent years, the finite element has achieved excellent results in the research of life sciences. For example, after long-term labor evolution, human bones have become an almost perfect mechanical structure. However, mechanical experiments cannot be carried out directly when conducting mechanical research on the human mechanical structure. Simultaneously, simulating mechanical experiments with finite elements has become an essential method in the aspect of steel plate fixation in HTO surgery [29]. The mechanical finite element method can be used to determine the best fixing method from the magnitude and angle of the stress. This dramatically improves the accuracy and efficiency of the operation, which helps with actual clinical problems.

In HTO surgery, the full-length specimens of the lower limbs are difficult to obtain, reducing the difficulty, and the height of the biological testing machine cannot accommodate the entire lower-limb specimens, so it is challenging to apply biomechanics to the full-length experiments of the lower limbs [30]. The finite element method can be designed for complex experiments. Time analysis of multiple optimal variables and multiple measurements, the experimental data obtained is comprehensive, so the application of finite element analysis of the biomechanical indicators of the full-length lower limb is the choice.

Finite element simulation also provides biomechanical support for surgical design. Use CT and MRI scans of the patient to establish a knee joint model, align it for finite element simulation calculations, and calculate the stress at any position. Compare the changes in the internal stress of the knee joint after surgery, which can provide a biomechanical basis for the results of the surgery. Now, this method has been gradually promoted and accepted. The reform of computers in recent years has dramatically reduced the time required for finite element analysis.

# Chapter 3 Model and methods

Knee joint CT and MRI scans of a young male's left lower limb were used to develop the bone and soft tissue structure. CT and MRI image data were imported into Mimics software (version 16, Materialise NV, Leuven, Belgium). Three-dimensional bone reconstruction was separated by the gray value of the tissue and the segmentation of the region. Subsequently, the contours of the articular cartilage (femoral, tibial, and fibula), meniscus (medial and lateral), and ligament (medial collateral, lateral collateral, anterior cruciate, and posterior cruciate) were segmented from the MRI images. The point cloud data of the TomoFix fixation system (1 T-shape plate and 8 locking screws) was obtained using a 3D scanner machine, and the data was imported into Geomagic DesignX software (version: 2016, 3D systems Korea, Seoul, Republic of Korea) to form solid models. All the models were exported as stereolithography (STL) files and were incorporated into 3-Matic 11.0 software (Materialise) for smoothing and alignment. All the solid models were imported into Hypermesh software (version: 14.0; Altair Engineering, Troy, MI, USA) to generate an FE mesh. Knee joint FE models were imported into Abaqus software (version: 2019; Simulia, Rhode Island, USA) to do simulation

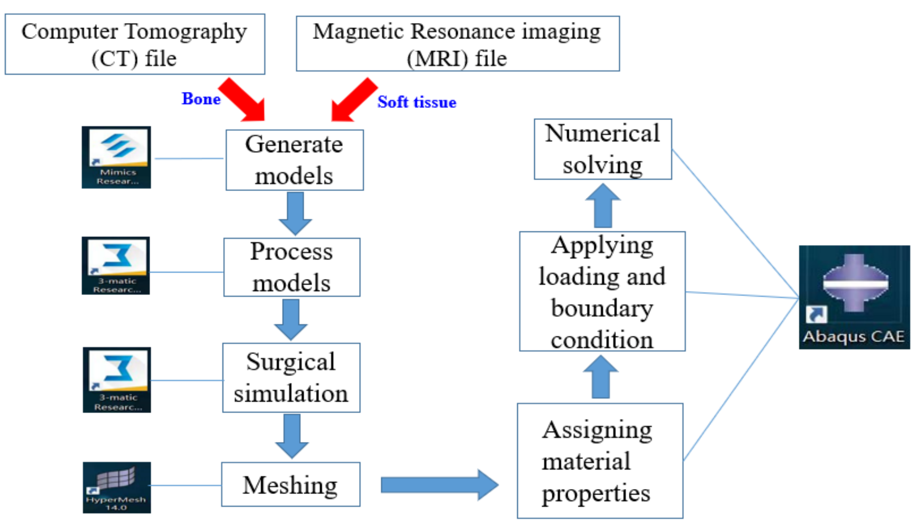
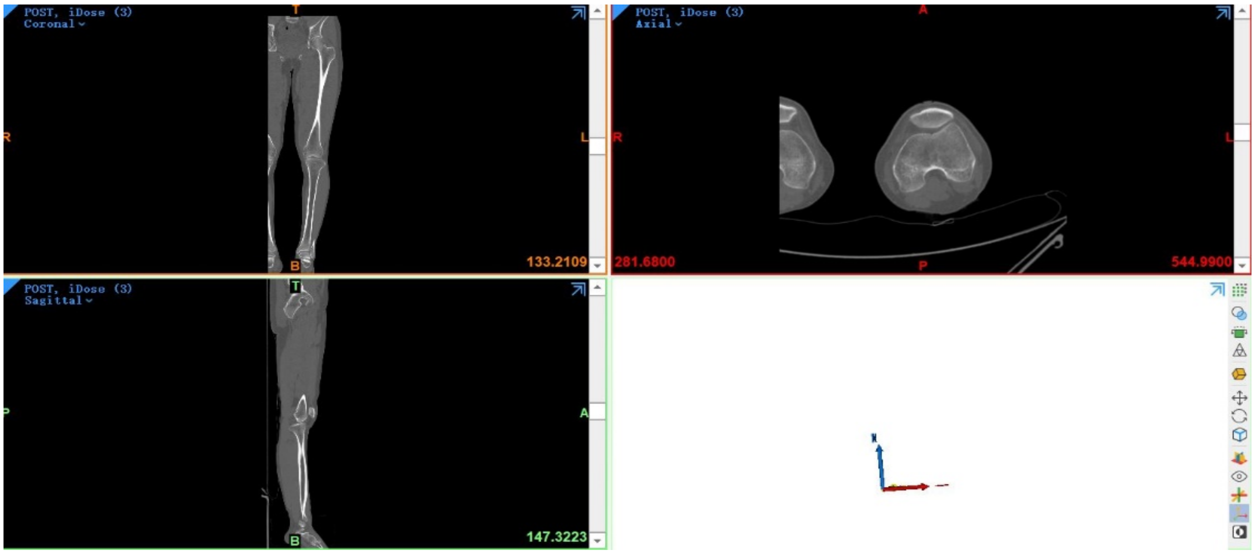



Fig10. Overview of the methodology

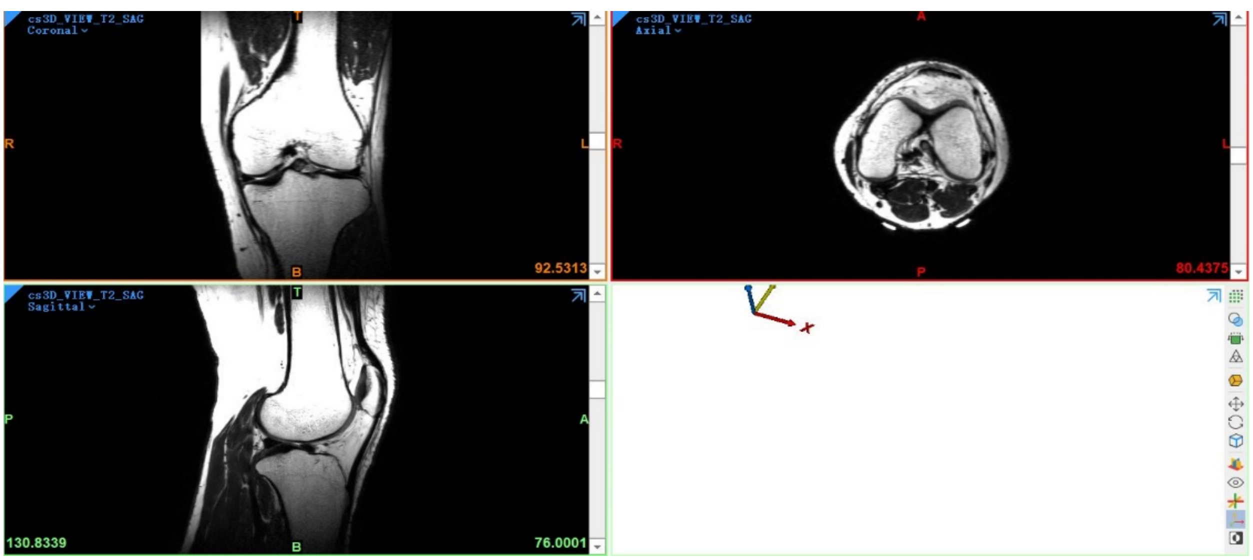
## 3.1 CT and MRI scan

The lower extremities were scanned using the SOMATOM Definition Edge 64 CT machine from Siemens, Germany. We scanned the entire lower extremity from the femoral head to the ankle. All the scans were 1mm thick, and the two-dimensional CT (Computer Tomography) images were obtained with 1,040 slices. The storage format is DICOM（Digital Imaging and Communications in Medicine）. Image was exported to a mobile device.

Knee joint CT and MRI scans of a young male's left lower limb were used to develop the bone and soft tissue structure. CT and MRI image data were imported into Mimics software (version 16, Materialise NV, Leuven, Belgium). Three-dimensional bone reconstruction was separated by the gray value of the tissue and the segmentation of the region. Subsequently, the contours of the articular cartilage (femoral, tibial, and fibula), meniscus (medial and lateral), and ligament (medial collateral, lateral collateral, anterior cruciate, and posterior cruciate) were segmented from the MRI images. The point cloud data of the TomoFix fixation system (1 T-shape plate and 8 locking screws) was obtained using a 3D scanner machine, and the data was imported into Geomagic DesignX software (version: 2016, 3D systems Korea, Seoul, Republic of Korea) to form solid models. All the models were exported as stereolithography (STL) files and were incorporated into 3-Matic 11.0 software (Materialise) for smoothing and alignment. All the solid models were imported into Hypermesh software (version: 14.0; Altair Engineering, Troy, MI, USA) to generate an FE mesh. Knee joint FE models were imported into Abaqus software (version: 2019; Simulia, Rhode Island, USA) to do simulation




(a)




(b)

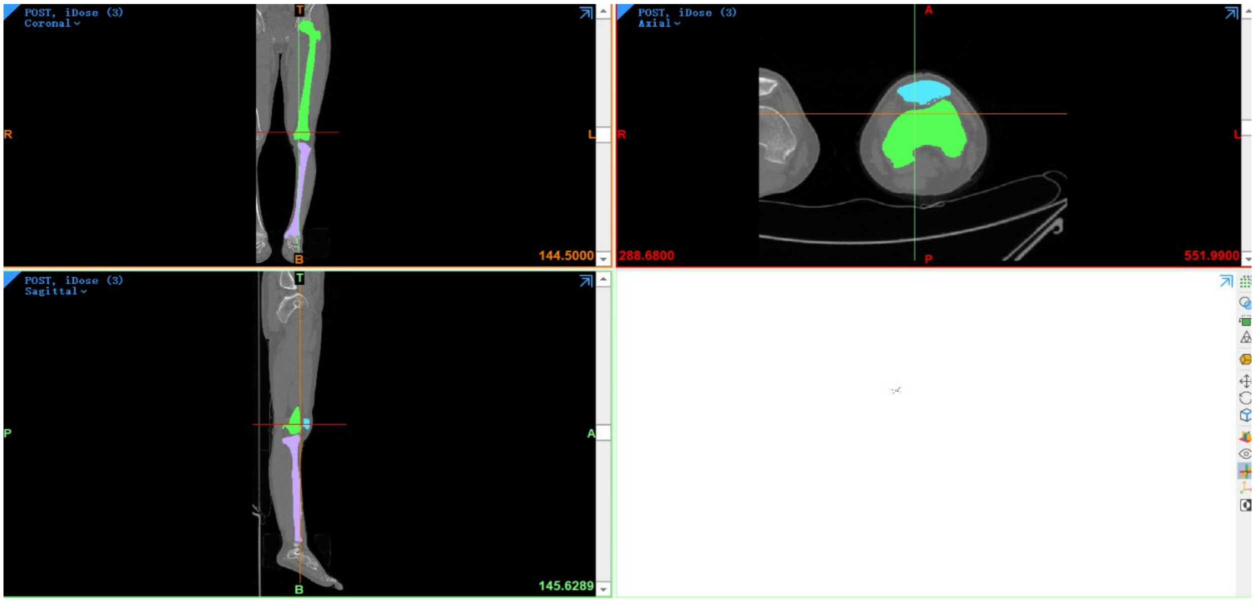
Fig11. CT and MRI image (a): CT image in Mimics software (b): MR image in Mimics software

## 3.2 Modeling of the knee joint

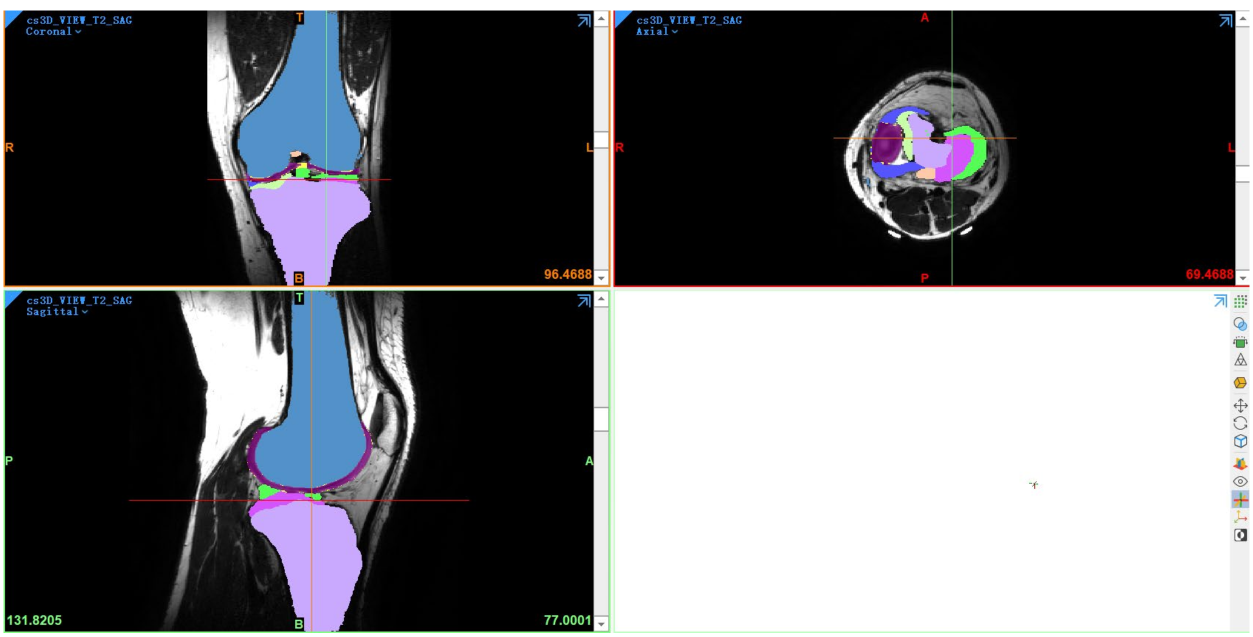
The CT and MRI image data were imported into Mimics software (version 16, Materialise NV, Leuven, Belgium). CT images are mainly used for the three-dimensional reconstruction of bone tissue. Open the CT scan in the Mimics 21 software. At this time, the images can be edited on the horizontal, coronal, and sagittal planes. The image can be segmented according to the gray value of each position to establish different bone models. The system displays different gray values according to different organizations and separates different gray areas according to Thresholding to outline the target image on three planes. The target image is often not accurate enough. At the junction of bone and soft tissue, the computer is often inaccurate or unable to recognize the situation. Therefore, the researcher needs to identify the edge of the bone with the naked eye and pass the tools such as Region Growing, Edit Masks, Cavity Fill. Finely we have adjusted the selection and selected the bone area judged by the naked eye. It can be observed whether the selection is made through the instant-generated 3D preview image. We used the two-dimensional image to confirm the fine adjustment of the edge and finally reconstruct an independent three-dimensional model of the required bone and used the STL grid. The formula is saved on the computer. The main bone structures of the modeled objects include the complete femur, tibia, and fibula.

The MRI image process is similar to the image of CT, and it is mainly used to model the reconstruction of soft tissue related to the knee joint. First, we extract each part according to the different gray values of each position of soft tissue. It created lateral meniscus, medial meniscus, femoral cartilage, tibial- fibula cartilage, ACL: anterior cruciate ligament, PCL: posterior cruciate ligament, MCL: medial collateral ligament, and LCL: lateral collateral ligament, respectively.

To facilitate the registration of soft tissue and bone, bone models need to be established in MRI. After all, knee joint models are established, using the registration function in MIMICS to mark feature points on CT and MRI scans. The more marked points, the better the registration. After the CT and MRI are fully registered, position is adjusted slightly to make each part fully conforming to the anatomical structure.




(a)




(b)

Fig12. Segment soft tissues and bone models (a): segment bone models based on CT images (b): segment soft tissues models based on MR images

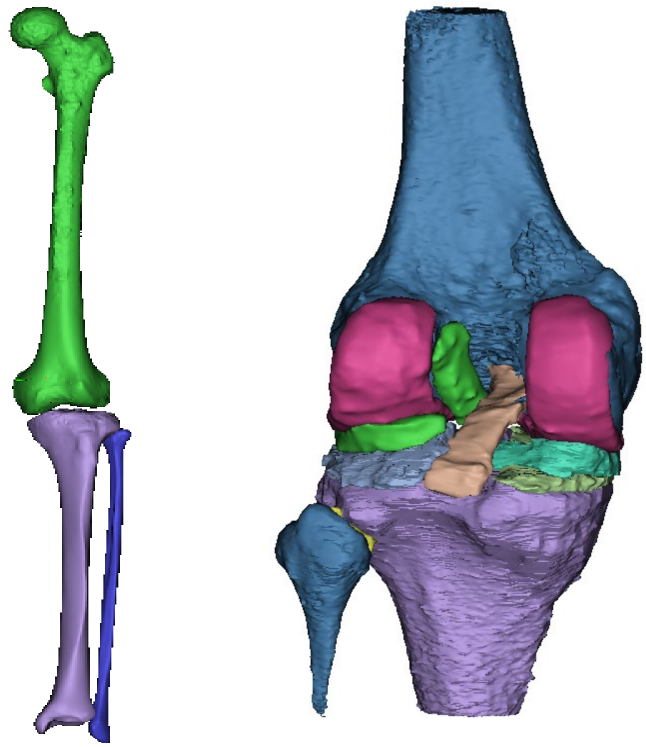


Fig13. Reconstructed bone and soft tissues models

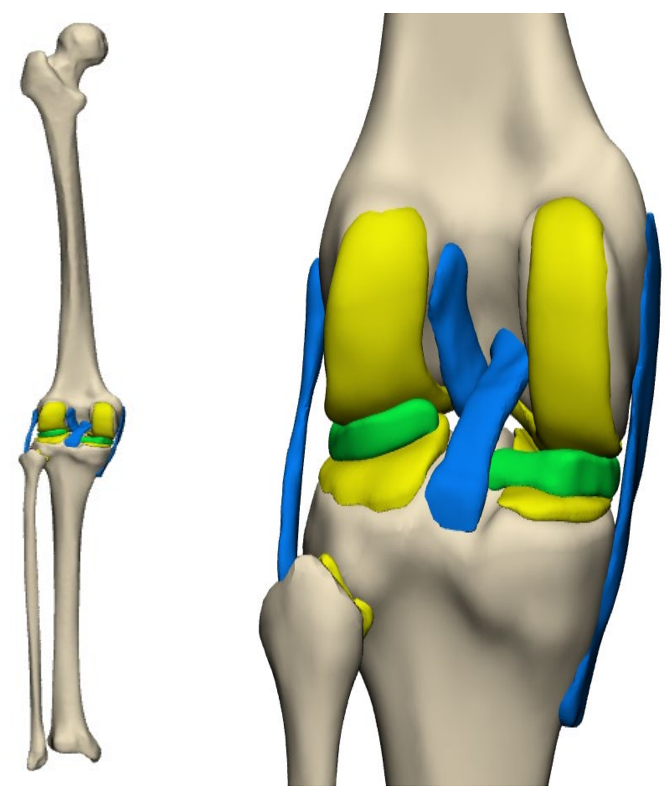


Fig14. Bone and soft tissues models registration

All the models were exported as stereolithography (STL) files and were incorporated into 3-Matic 11.0 software (Materialise). Process for each part of the model was performed separately, trying to make the surface of each part smooth and uniform in thickness, and avoiding sharp corners. This is because various situations such as stress concentration and failure of stress transfer will occur when the mesh is drawn in the later stage. In the 3-Matic software, the model is processed with multiple functions: fixing, shrinking, wrapping, and meshing. Parts of the model should be relatively smooth. 2D mesh was drawn in 3-Matic advance to facilitate 3D mesh division later. After processing each model, all models will be registered. The bones and soft tissues are registered, as shown in the figure.

Solid TomoFix plate was scanned (1 T-shape plate and eight locking screws) with a 3D scanner and the obtained data was imported into Geomagic DesignX software (version: 2016, 3D systems Korea, soul, Republic of Korea) to generate a solid model (Fig.15).

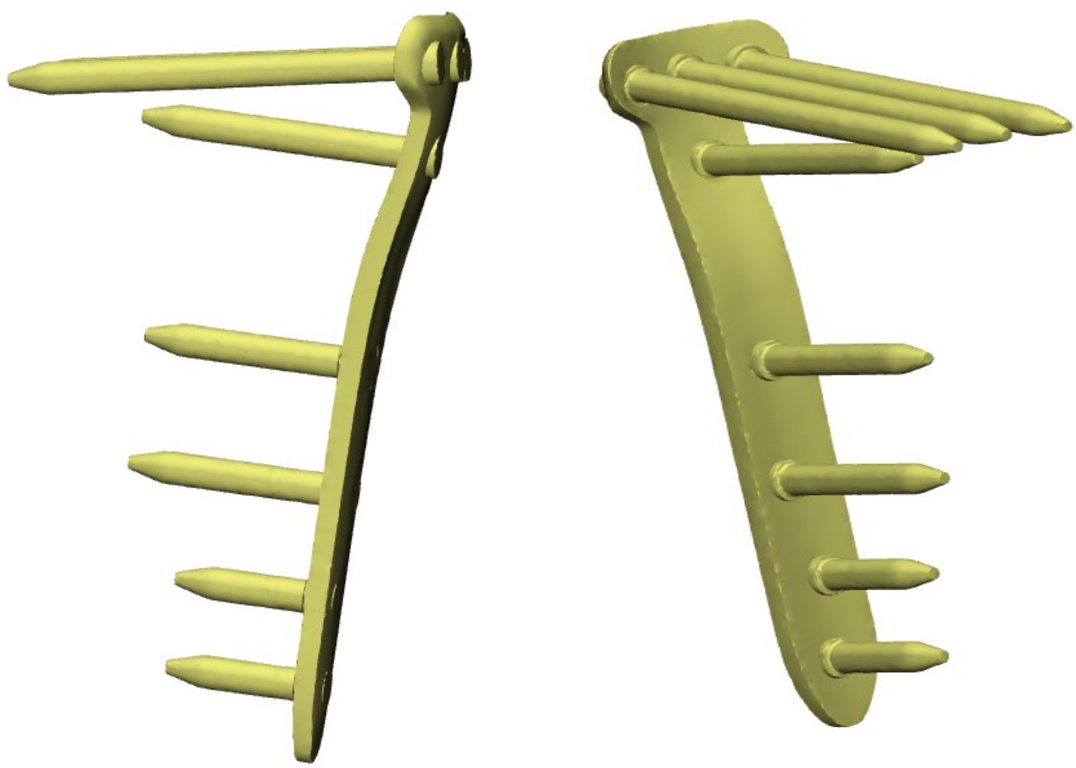


Fig15. TomoFix plate & screws registration

# 3.3 FE model

## 3.3.1 Meshing

All solid models were imported into Hypermesh software (Version: 14.0; Altair Engineering, Troy, MI, USA) to generate FE mesh. Because the 2D mesh has been checked in 3-Matic, there is no need to process the model in Hypermesh. However, if the model is defective, it needs to be reprocessed in the 3-Matic software. After importing to the Hypermesh, first each part is named according to the position. Then, it is to have 2D meshes, and the meshes that do not need to be refined are divided into 2mm size. For the cartilage meniscus and other parts in contact with other models, the size of 1mm will be used to mesh. Due to the incremental update of modern computers, computer algorithms have been strengthened. Therefore, the influence of tetrahedral and hexahedral mesh on the finite element results gradually decreases, so the meshes in this article are all tetrahedral mesh.

After meshing all models into 2D meshes in Hypermesh, meshing 3D meshes under tetramesh in the 3D module. If the model is not closed, the model mesh will fail. Therefore, it must be ensured that the 3D mesh is divided under closed conditions. The 3D mesh generates a volume mesh based on the plane divided by the 2D mesh. After the volume mesh is divided successfully, the two-dimensional grid is deleted that we initially divided.

After submitting a job in ABAQUS, errors are often reported due to grid problems. After an error is reported in the ABAQUS software, we need to check the error grid on the result page and re-import Hypermesh to process the mesh. Then we adjust the size and angle of the error grid in Hypermesh and delete the too-small grid. Moreover, it can be also edited in the INP file exported by ABAQUS. The grid problem is the key to the success of the finite element analysis. Good grids often reduce calculation time and improve accuracy. When dividing the grid, it is not that the smaller the grid is, the better. Too small grid will only increase the calculation time and is not conducive to analysis and calculation. The appropriate mesh size is also significant for finite element analysis.

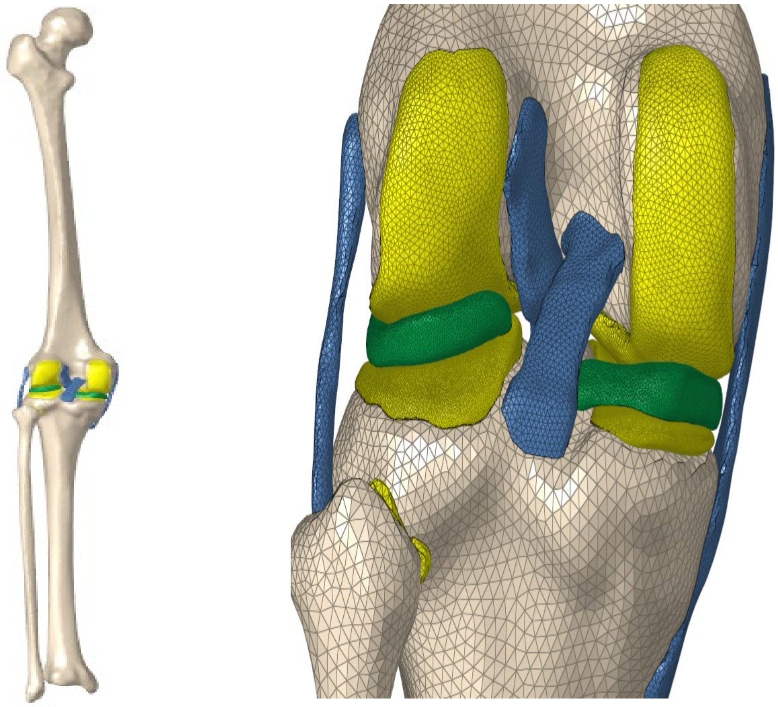


Fig16. Knee joint mesh model

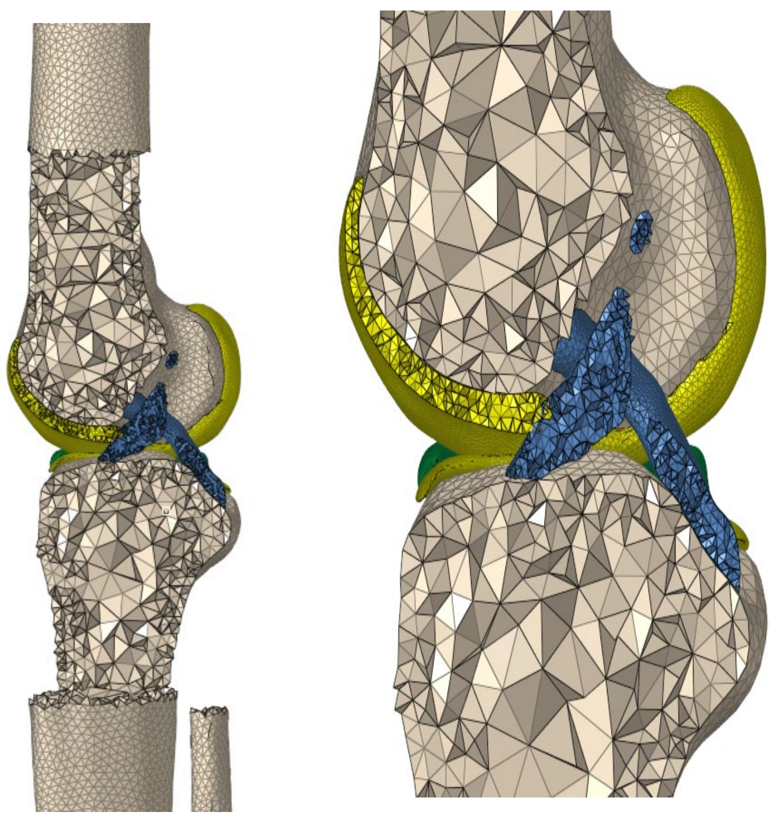


Fig17. Volume mesh

## 3.3.2 Material properties contacts

Healthy knee joint FE models were imported into Abaqus software (version: 2019; Simulia, Rhode Island, USA). Assigning material properties to the model is one of the most critical steps to ensure the accuracy of the finite element results. The material properties of soft tissues and bones have always been one of the conservatively controversial topics. However, through recent years of biomechanics research, the data results obtained are getting closer and closer to reality. For this article, we use simplified linear elastic material properties for research. Moreover, this article deals with a complete lower limb model for simulation, so the influence of cortical and cancellous bone was negligible.

The bone, screw, and plate were considered linearly elastic, homogenous, and isotropic. The elasticity and Poisson's ratio of the bone were 8 GPa and 0.3, respectively. [14] The Tomofix plate and screw were made of titanium alloy for which Young's modulus is 110 GPa and Poisson's ratio is 0.3. [15] The incompressible nature under short loading time of articular cartilage and meniscus was considered single-phase linear elastic and isotropic material. [16] The material properties for these two soft tissues were E=5 MPa, v=0.46 and E=59 MPa, v=0.49, respectively. [17] The elastic modulus and Poisson's ratio of the four major ligaments were 45 MPa and 0.48, respectively. [18] The properties of structural materials are shown in Table 1.

**Table 1** Material properties used for this study

| Items | Elastic modulus (MPA) | Poisson's ratio |
|---|---|---|
| bone | 8000 | 0.3 |
| cartilage | 5 | 0.46 |
| meniscus | 59 | 0.49 |
| ligament | 45 | 0.48 |
| plate+screw | 110000 | 0.3 |

There is no friction between the meniscus of the knee joint and the tibial cartilage, and the meniscus is attached to the tibial cartilage [31]. Therefore, we use the Non-manifold Assembly method for the contact between the meniscus and tibial cartilage. First, we adopted an unpopular assembly method in 3-Matic software. First, we connected the nodes on the meniscus and tibial cartilage to each other. Then we removed the protruding sharp corners and handled the model. Next, we imported the processes into the Tool module in Hypermesh and used the edge command to fit and finally imported the 3D module to mesh the volume mesh.

Since the contact between bone and cartilage is wholly attached, in the Abaqus interaction module, we designate femoral-femoral cartilage, tibia-tibial cartilage, and fibula-fibular cartilage as TIE contact. The movement of each part of the ligament is similar to cartilage. So, in Abaqus, we also contact ACL, PCL, MCL, LCL, TIE, respectively. The friction between the femoral cartilage and the meniscus is relatively tiny. Each does not limit the scope of each other's activities. So, we define it as face-to-face contact. The coefficient of contact friction is 0.064 [32].

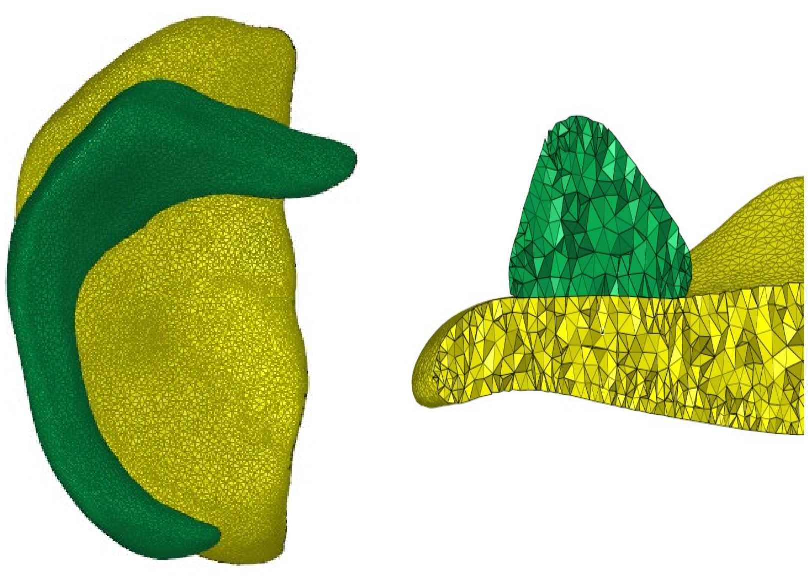


Fig18. Con-node used in this study

## 3.3.3 Loading and boundary conditions

First, we create a reference point above the femoral head center under the interactive module in Abaqus to fully couple it to the femoral head. And then we limit the degree of freedom of the proximal femur's X, Y, and Z axes. The femur does not move in the flexion direction in daily life, so we limit the flexion direction. The distal fibula and tibia also do not move in daily life, so the distal tibia and the distal fibula are entirely fixed in degrees of freedom [33]. Next, we create a coordinate system at the center of the distal tibia. Finally, we create a line between the center of the femoral head and the center of the distal tibia, which completely simulates the force state of the lower limbs when standing on one leg [34].

The distal ends of the tibia and fibula were fixed in the HTO surgical simulation. The angle of flexion is fixed when the femur is extended fully. [35] Femoral cartilage and femoral cortical bone were in bound together, as were the tibial cartilage and the tibial cortical bone. All ligaments were attached firmly to the corresponding bone to simulate bone-ligament attachment. [36] The meniscus and the upper part of the femoral cartilage were set in a frictional relationship at a friction coefficient of 0.064. A compressive load of 1150 N (two body weights) was applied on the femoral center of mass. The compressive load was transmitted through the weight-bearing line from the femoral head center to the ankle joint center (Fig.18).

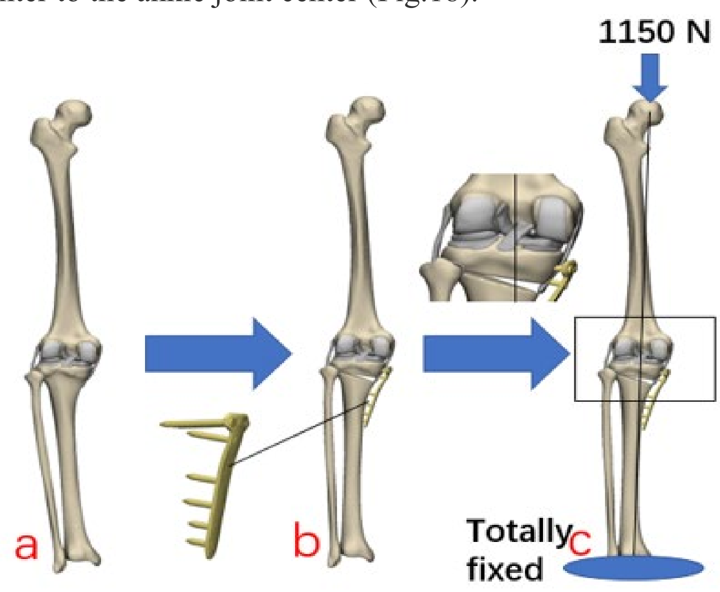



Fig19. Simulation design process (a):7° varus patient model (b): HTO model (c): loading and boundary conditions

## 3.4 Patient knee joint

By simulating tibial varus in Abaqus, the model of tibial varus patient was constructed. To make a better model of tibial varus patients, we discussed with experienced orthopedic doctors and finally made a plan. First, we import Abaqus and created a point by fully fixing the femur and the center of the tibial plateau to the reference point. The reference point will be coupled with the tibial plateau.

Healthy knee joint FE models were imported into Abaqus software (version: 2019; Simulia, Rhode Island, USA) to achieve a 7-degree varus simulation. The ODB data file was imported into the 3-Matic for processing and re-meshing. We split each part and named it. During the simulation process, the meniscus and tibial cartilage were squeezed severely. Therefore, it is necessary to smoothly squeeze the more severe parts to make all the models more rounded. Furthermore, we check the model defects in 3-Matic. Sharp edges and distorted surfaces were avoided. Finally, we import the processed model into Hypermesh for meshing.

Meshing in Hypermesh also divides a 2D surface mesh first and then generates a 3D volume mesh based on the 2D surface mesh. The mesh size is the same as that of the normal human model, and the tetrahedral mesh is also used for mesh in Hypermesh software (Fig.19).

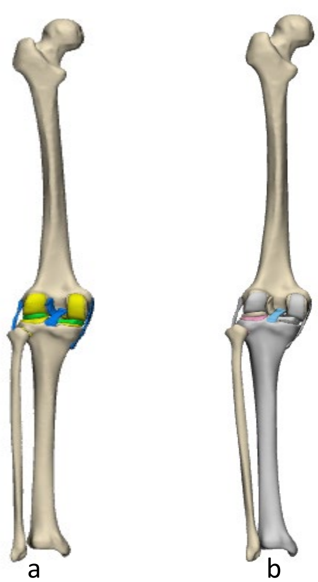



Fig20. Knee joint model of healthy human and patient (a): healthy human knee joint model (b): 7° varus patient knee joint model

## 3.5 Surgical of the knee joints

The model was tested under the supervision of an experienced orthopedist. An opening wedge side was created to simulate HTO surgery using 3-Matic, while the wedge size and correction angle were as described in previous studies.

The size of the osteotomy for high tibial osteotomy varies significantly from patient to patient [37]. Moreover, it is challenging to study actual surgery, so this article will stimulate the operation process in 3-Matic software and introduce the approximate operation size. First, we took the highest point on the outer side of the patient's tibial plateau and drew a straight line. We Selected 35mm from the inner side of the tibial plateau as the opening position. Then it would be the best if determined the hinge position [37]. The tibia should be proximal to the lateral cortex for open tibial osteotomy, approximately on the upper tibia. The upper edge of the fibular joint is about 10-15mm below the lateral platform. For the osteotomy line, it is necessary to have enough fixation of the tibial structure, and the hinge position is relatively good, which is conducive to healing and other characteristics (Fig.20)

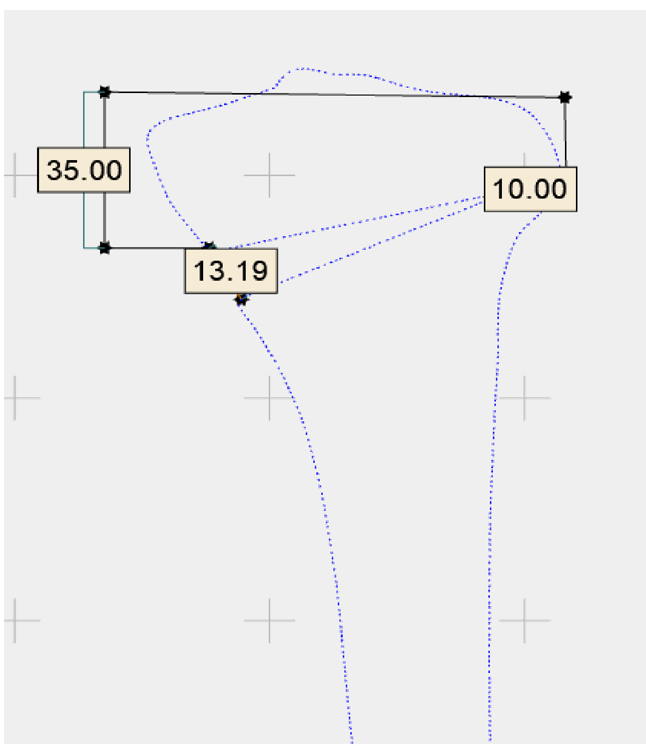



Fig21. Sketch of the tibia

After obtaining the hinge position, we used this point as the center of rotation and the distance from the ankle joint center to the hinge was taken as the radius to rotate until it crosses the target force line. The angle of rotation is the angle that needs to be corrected. For the side where the wear is severe, the weight-bearing line needs to be relatively offset [38]. When the tibia is processed, the TomoFix plate will be implanted, and the TomoFix plate is connected to the tibia at a con-node contact (Fig21).

Finite element knee models were established with HTO and three types of undercorrection (three models), neutral position (one model), and overcorrection (three models) based on correction angles (Fig.22). To research the effect of correcting the angle on HTO surgery we have respectively made over-corrected and under-corrected knee joint models. Correcting the angle too much will cause the operation to fail and correcting the angle too small will not have an excellent surgical effect. Therefore, proper angle selection is essential in HTO surgery. According to the different HKA angles, this study is divided into overcorrection of one degree, two degrees, and three degrees, and undercorrection of one degree, two degrees, and three degrees.

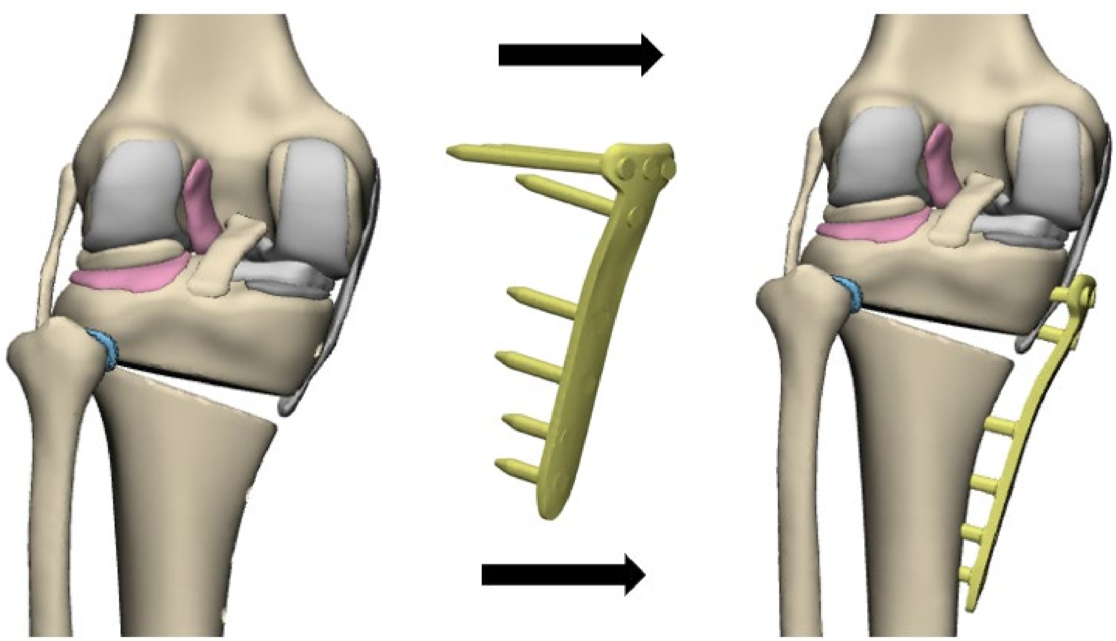


Fig22. Insertion of the plate, screws, and bone-graft substitute

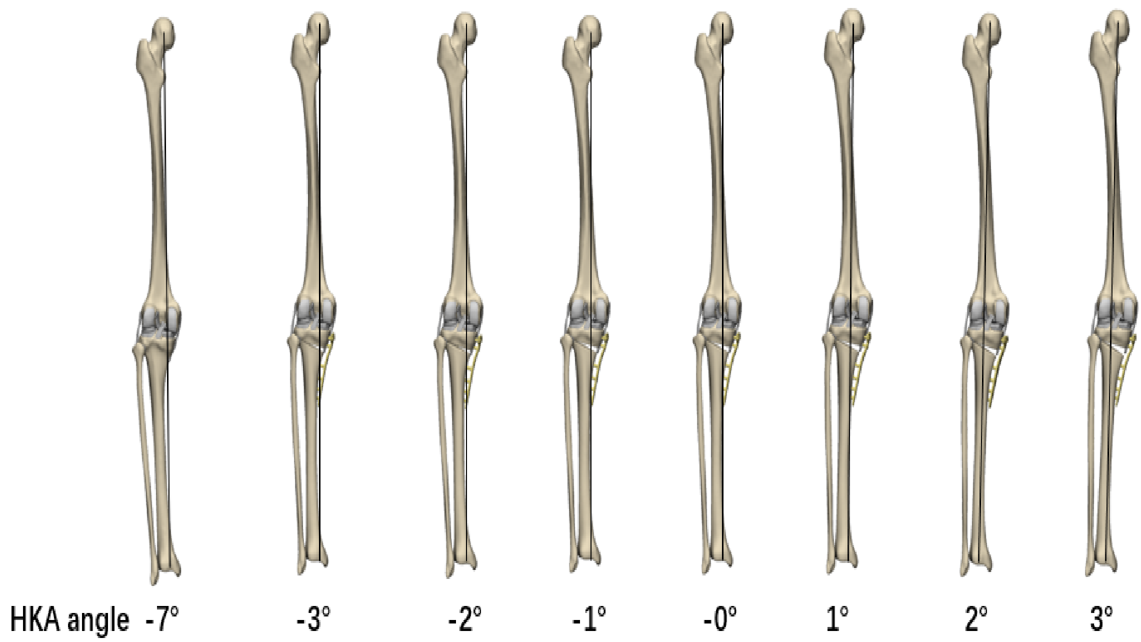



Fig23. HKA angles before and after HTO

# Chapter 4 Results and discussion

Finite element analysis can obtain the stress distribution on the optional position. Then, the surgery results of the operation are evaluated by the stress distribution. In this study, the Von Mises stress is mainly used to determine the magnitude of the stress. In addition, contact pressure was calculated for comparing the results with the previous studies to validate the models.

Firstly, we performed the stress analysis of the lower limb model of a healthy human and analyzed the stress distribution of each part. The simulation results of healthy people can be used for model verification and comparison of effectiveness after surgery. After that, we compared the results before and after HTO surgery to check the biomechanical effectiveness of HTO surgery by repeatedly comparing the changes in Von Mises stress, contact stress and shear stress. Finally, to optimize the effect of HTO we designed multiple models to simulate the operation situation of different HKA angles after the operation. According to the results of the biomechanical simulation, we summarized the optimal surgical osteotomy angle.

# 4.1 Modeling validation

For FE model validation contact pressures of the medial and lateral meniscus were checked under the loading condition of axial load 1150N. The contact pressures of the medial and lateral meniscus are 2.846MPa and 3.376MPa, respectively (Fig.24). The lateral stresses are distributed in the anterior and posterior corners of the meniscus, and the stresses on the medial meniscus body are the largest. The results were similar with the contact pressures corresponding to 3.15MPa and 3.68MPa reported by Peña et al (Fg.23). The differences may be caused by individual differences, geometrical model differences such as the shapes of the cartilage and meniscus between different studies. However, on an overall basis, the consistency between the validation result and previous studies confirmed the ability of the present model to produce convincing results.

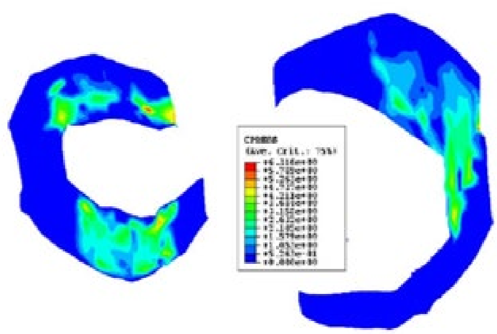


Fig24. Stress distribution on the meniscus in previous study

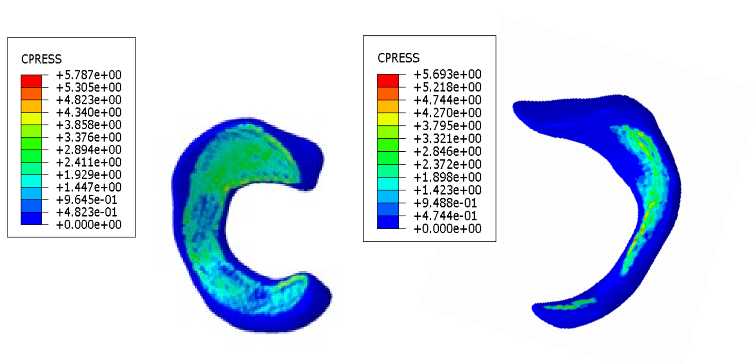



Fig25. Stress distribution on the meniscus in this study

## 4.2 Results

## 4.2.1 Stress distribution at normal knee joint

Figure 25 shows the simulation analysis results of healthy human lower limbs. Under vertical load, the external force of the femoral cartilage is slightly greater than that of the medial side, and the maximum stress value of the femoral cartilage is 1.181MPa, which appears in the lateral area. The femoral cartilage interacts with the meniscus and tibial cartilage. The contact area with the meniscus is more extensive, and the stress of the contact area is greater than the stress of the tibial cartilage. The force on both sides of the meniscus is even, and the medial meniscus is slightly higher than the lateral meniscus. The meniscus transfers stress between cartilage, and the stress of the meniscus is higher than the stress of cartilage. Ligament plays the role of fixing the knee joint. Especially the cruciate ligament is fragile and bears greater force. The stress of the cruciate ligament is greater than that of the bilateral collateral ligaments when the typical knee joint is subjected to a vertical load. The maximum stress value of the knee joint appears on the cruciate ligament, and the maximum value is 6.32MPa. For the cruciate ligament. The ACL is fully tensioned, and the maximum stress value is generated in part in contact with the tibia. For PCL, only the maximum tension of the front-end part is less than ACL. For the lateral collateral ligament. LCL is mainly out of compression. The load generated by MCL is more of shear-type stress distribution.

Simulation analysis results of normal people's knee joints were compared with the previous literature to verify the reliability of this study. It took the simulation of the normal knee joint and compared the results after the operation. This can well reflect the HTO surgery of the operation. Moreover, if the stress value is too significant to exceed the stress value of a normal person, it will cause unstable factors such as operation failure.

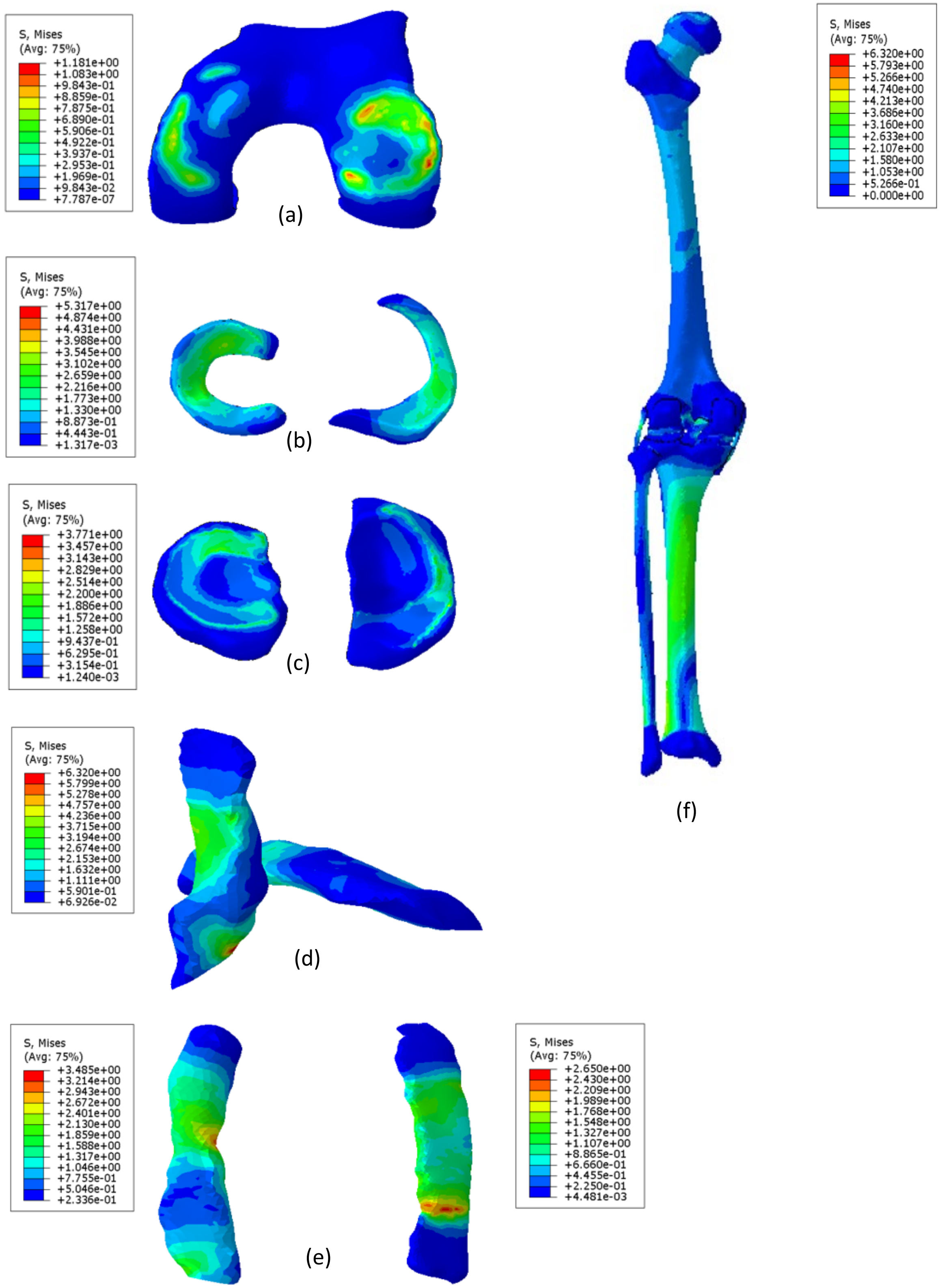



Fig26. The von Mises stress distribution the normal knee joint (a): femoral cartilage (b): meniscus (c): tibial cartilage (d): ACL, PCL ligaments (e) LCL, PCL ligaments (f): knee joint

## 4.2.2 Stress distribution on the knee joint before and after osteotomy

Figure 26 shows the stress distribution patterns of the knee joint before and after HTO surgery. The von Mises stress distribution reflects the change of stress before and after HTO. The HKA before HTO surgery was 7°, and the WBA passed through the medial tibia plateau. The medial compartment stress is much higher than the lateral stress. After the operation, the HKA angle changed from seven degrees to zero degrees. Therefore, the forces on both sides are balanced. However, due to the more significant stress on the hinge position of the osteotomy correction, it is very easy to damage and rupture. The maximum stress of the TOMOFIX plate after surgery is 97 MPa. This is because the TOMOFIX plate plays a role in fixing the tibia, and the force is relatively large.

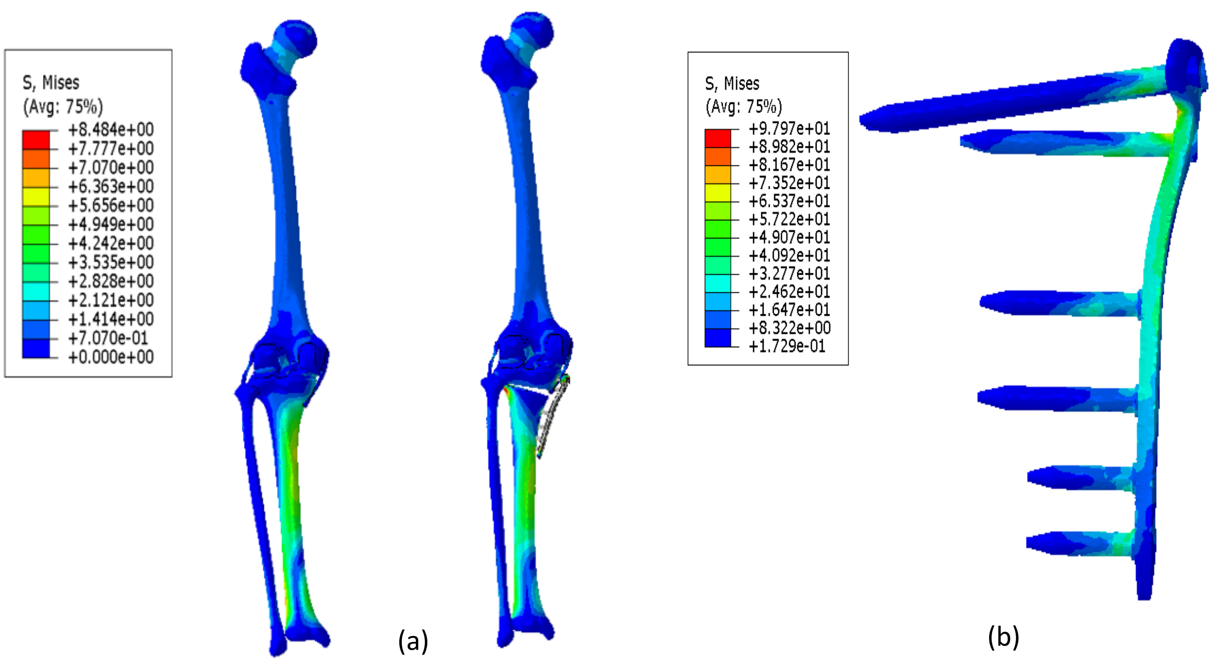



Fig27. The von Mises stress distribution the before and after HTO surgery knee joint (a): before HTO surgery Knee joint (b): after HTO surgery Knee joint (c): TOMOFIX plate

The femoral cartilage attaches to the femur and interacts with the meniscus and tibial cartilage. After HTO surgery, the stress on the lateral femoral cartilage was significantly reduced, and the lateral pressure was significantly increased (Fig28). Before the operation, the maximum Von Mises stress of the patient was 1.401MPa, the maximum contact stress was 5.575MPa, and the maximum shear stress value was 1.528MPa, all of which appeared on the outside. After HTO surgery, the maximum value of Von Mises stress is 1.322MPa, contact stress is 5.14MPa, and the maximum shear stress value is 1.452MPa. Thus, the Von Mises stress value is reduced by 5.6% through HTO operation. In addition, the contact stress value has been reduced by 7.8%, and the shear stress value has been reduced by 5%. Therefore, by the HTO surgery, the force condition has been significantly improved.

The meniscus interacts with the femoral cartilage and tibial cartilage, respectively. Therefore, the stress of the lateral meniscus increases significantly after the operation (Fig,29, Fig30). Before the operation, the maximum Von Mises stress of the lateral meniscus of the patient is 3.347MPa, the maximum contact stress is 4.744MPa, and the maximum shear stress value is 3.513MPa. The maximum von mises stress the value of the patient's medial meniscus before surgery is 8.484MPa, the maximum contact stress is 4.744MPa, and the maximum shear stress value is 9.445MPa. The lateral meniscus after HTO surgery. The maximum Von Mises stress is 4.919MPa, the maximum contact stress is 5.967MPa, and the maximum shear stress is 4.919MPa. The Von Mises stress of the lateral meniscus through HTO surgery has increased by 47%, The contact stress value increased by 25.8%, and the shear stress value increased by 40%. After the operation, the HKA angle of the lower extremity changed, and the force position of the medial meniscus also changed. After HTO surgery. The medial meniscus maximum Von Mises stress is 7.514MPa, the maximum contact stress is 8.309MPa, and the maximum shear stress value is 9.039MPa. The Von Mises stress value is reduced by 11.4% through the HTO operation, and then contact. The stress value is reduced by 9.3%, and the shear stress value is reduced 4.3%. After HTO surgery, the stress of the medial meniscus is significantly reduced, and the stress of the lateral meniscus is significantly increased.

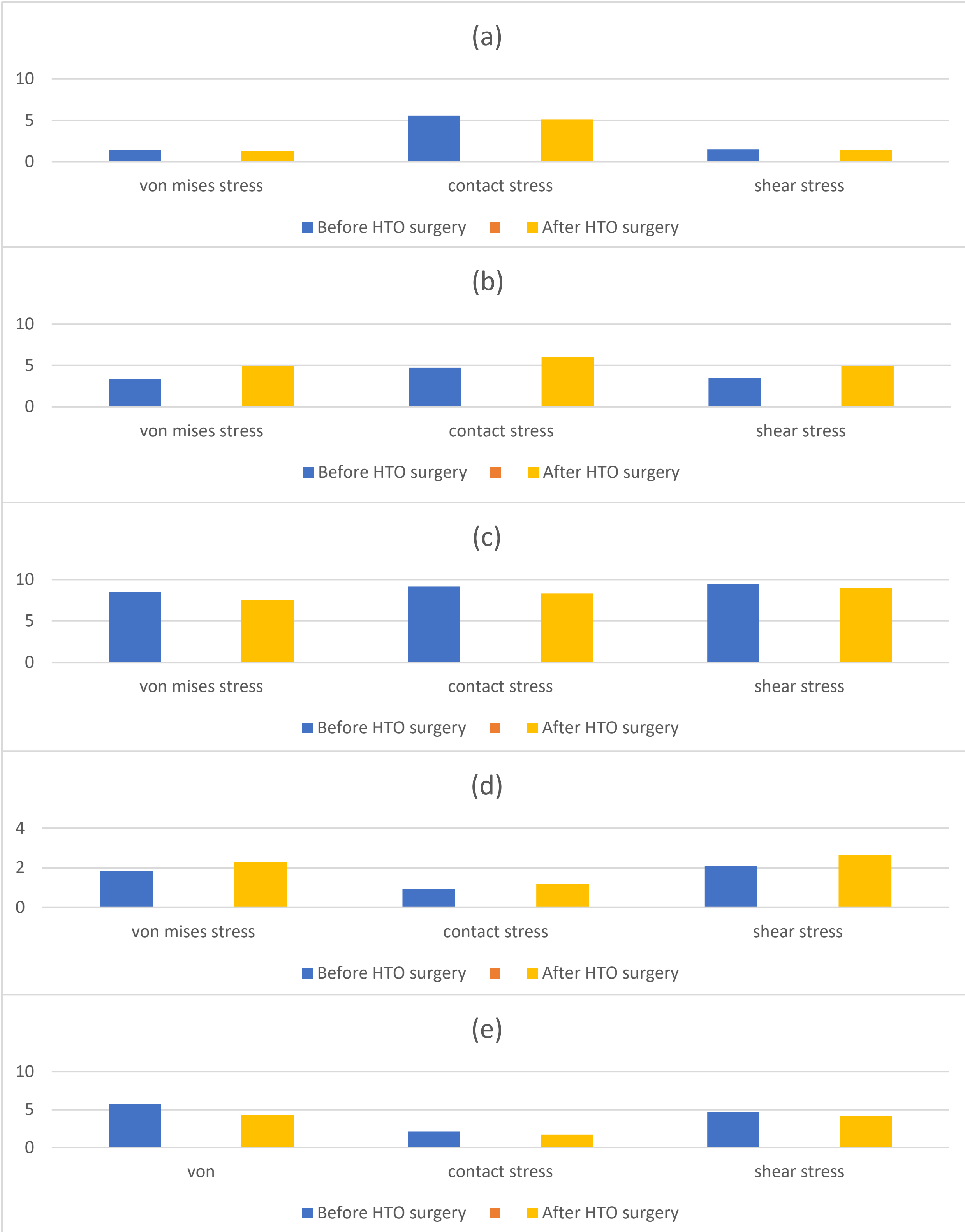



Fig28. Stress distribution in patient and HTO post operation on knee soft tissue (a): femoral cartilage (b): lateral meniscus (c): medial meniscus (d): lateral tibial cartilage (e): medial tibial

The tibia's medial cartilage and lateral cartilage attach to the femur and interact with the meniscus and tibial cartilage. It is also the most severely damaged site in patients with OA. As shown in Fig 31, Fig 32, the maximum Von Mises stress of the lateral tibial cartilage of the patient before surgery is 1.825MPa, and the maximum contact stress value is 0.961MPa, and the maximum shear stress value is 2.105MPa. Before surgery, the maximum Von Mises stress the value of the medial tibial cartilage of the patient is 5.779MPa, the maximum contact stress is 2.15MPa and the maximum shear stress value is 4.653MPa. After the HTO surgery, the lateral tibial cartilage maximum Von Mises stress is 2.297MPa, the maximum contact stress is 1.21MPa, and the maximum shear stress is 2.648MPa. The Von Mises stress of the lateral meniscus through HTO surgery has increased by 25.9%, The contact stress value increased by 25.1%, and the shear stress value increased by 25.8%. After the operation, the HKA angle of the lower extremity changed, and the stress position of the medial tibial cartilage also changed. The medial tibia after HTO surgery. The maximum Von Mises stress of cartilage is 4.252MPa, the maximum contact stress is 1.688MPa, the maximum compressive stress is 0.1114MPa, and the maximum shear stress is 4.167MPa. The Von Mises stress of the medial tibial cartilage is reduced by HTO surgery 26.4%, the contact stress value is reduced by 20.3%, the compressive stress value is reduced by 16.7%, and the shear stress value is reduced by 10.4%. After HTO surgery, the medial tibial cartilage is significantly reduced, and the lateral tibial cartilage stress is significantly increased.

High stresses were found in the medial compartment, and stress in the medial compartment of the tibia plateau was reduced after HTO. Areas of high stress moved from the medial to lateral compartment as the HKA was corrected. As the HKA was corrected, the femoral cartilage reduced contact with the medial tibial cartilage but with a similar contact area transition.

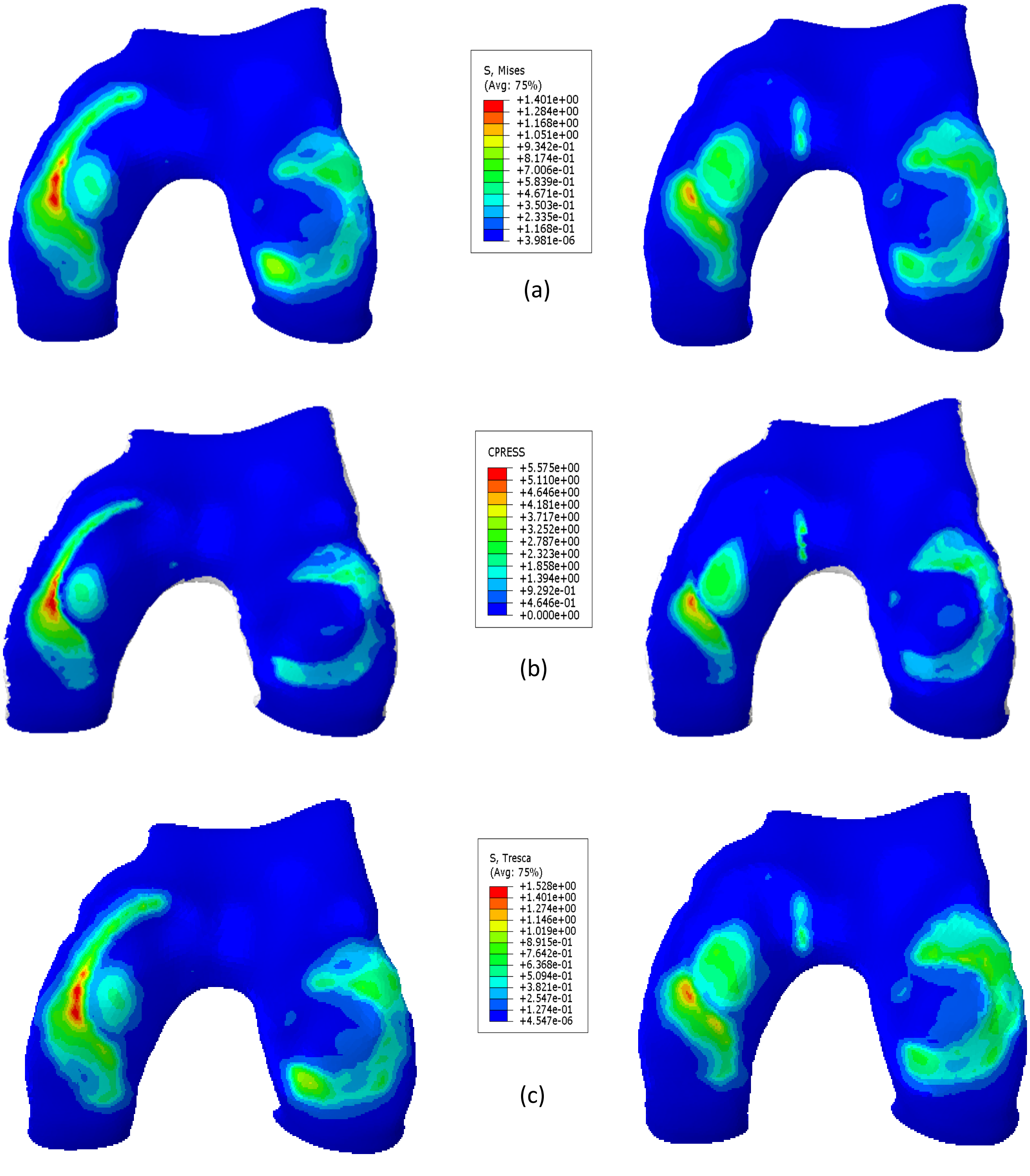



Fig29. Patient and post operation femoral cartilage indexes comparison (a): Von Mises stress (b): contact stress (c): shear stress

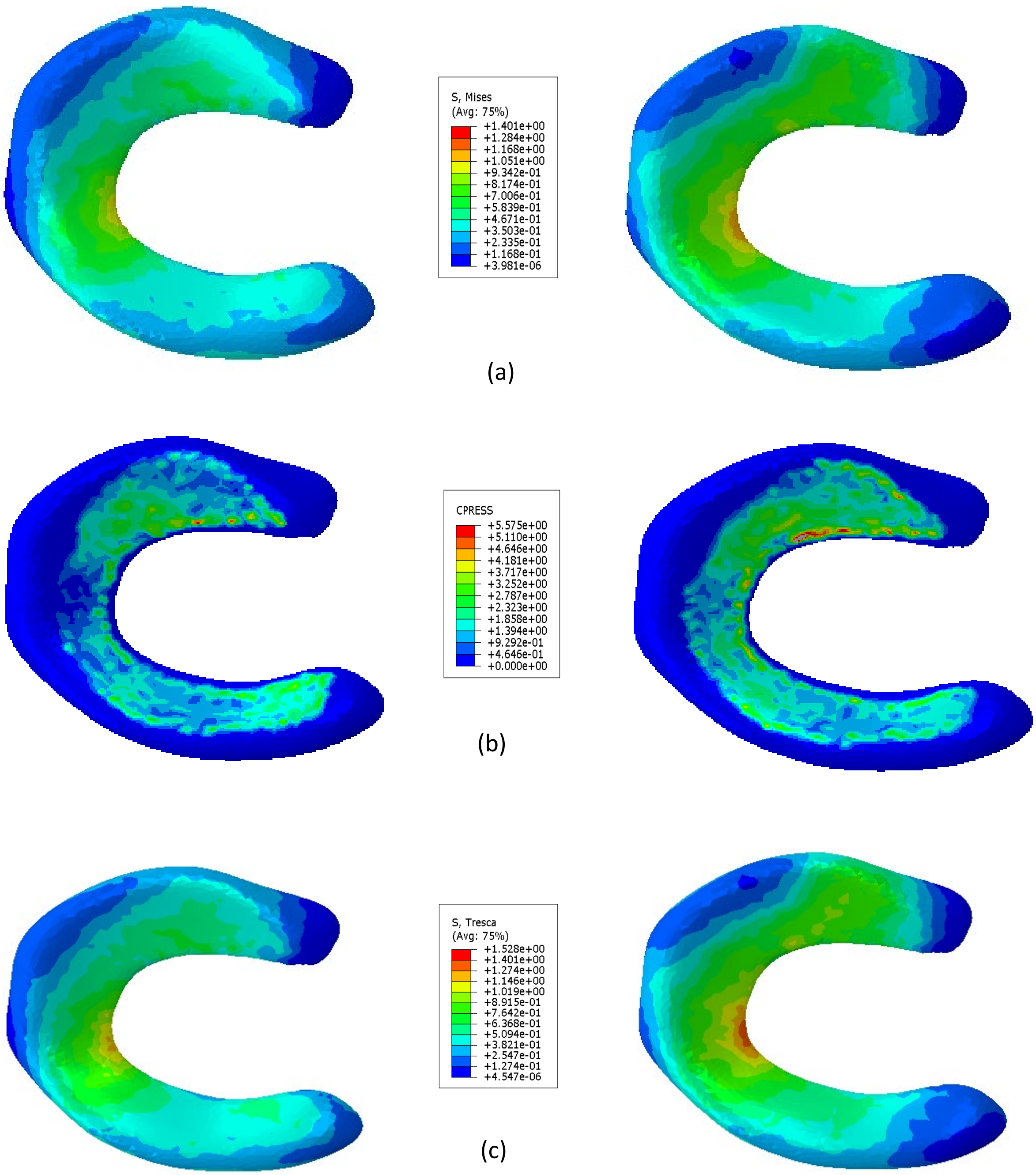



Fig30. Patient and post operation lateral meniscus indexes comparison (a): Von Mises stress (b): contact stress (c): shear stress

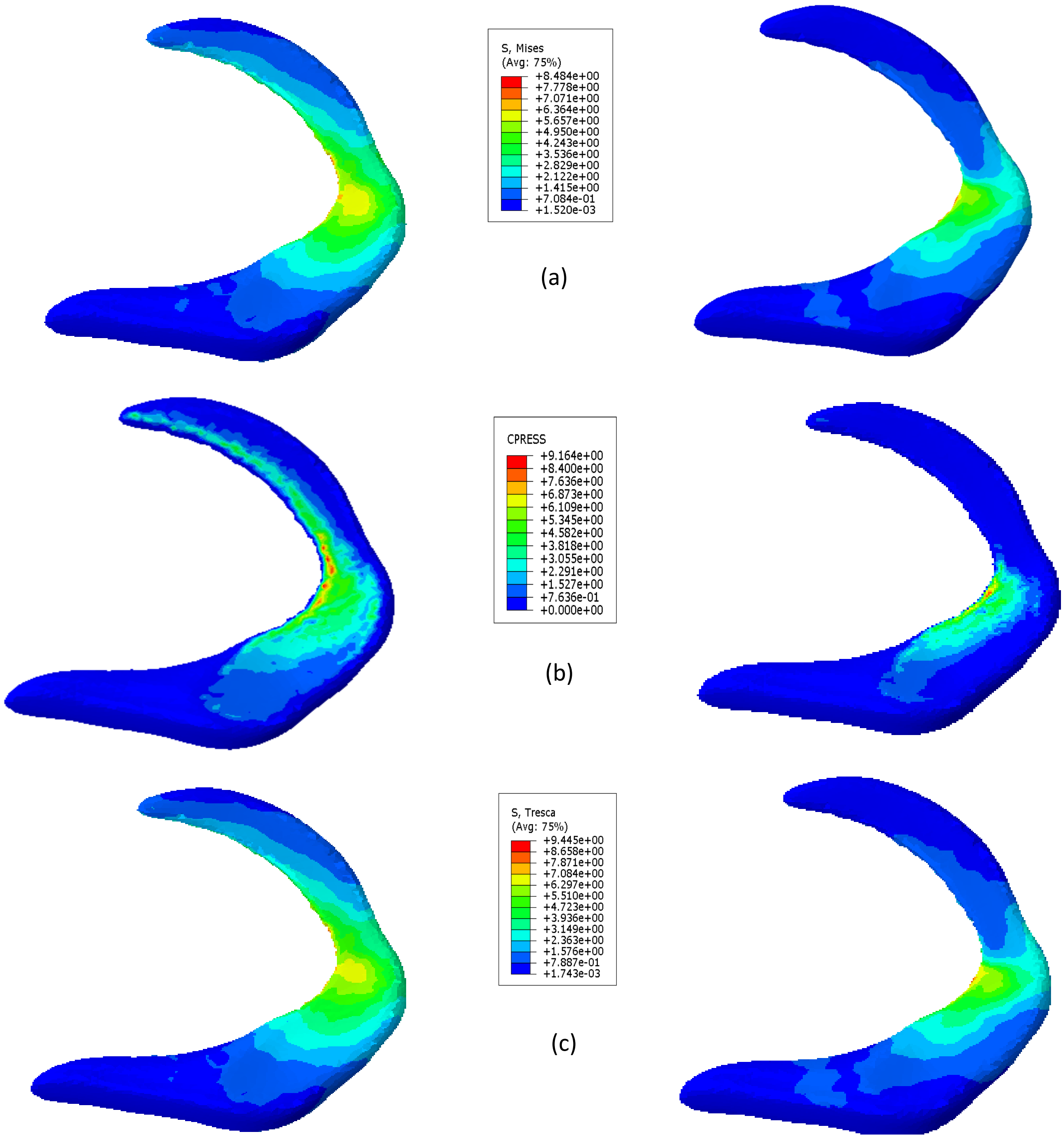



Fig31. Patient and post operation medial meniscus indexes comparison (a): Von Mises stress (b): contact stress (c): shear stress

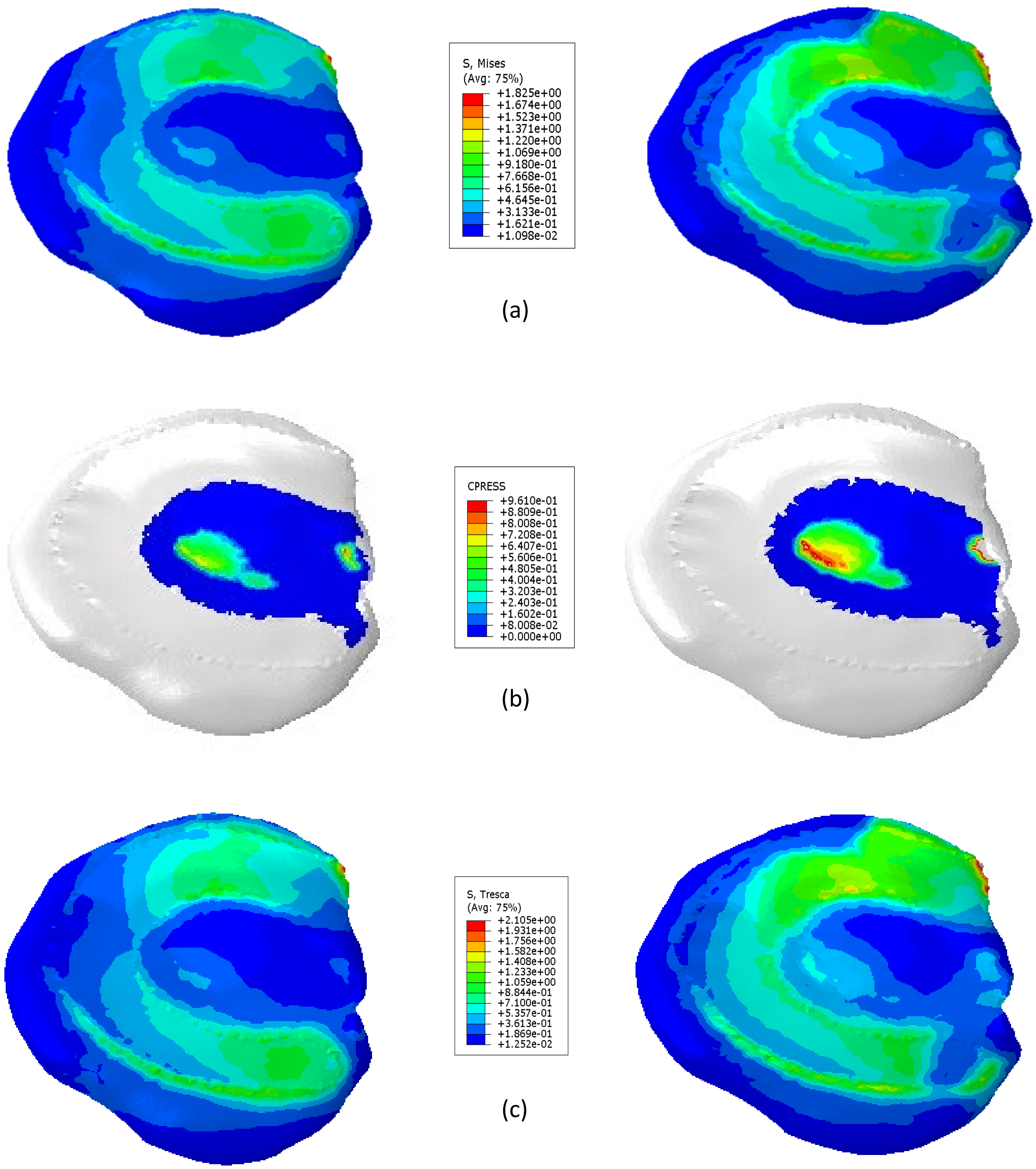



Fig32. Patient and post operation lateral tibial cartilage indexes comparison (a): Von Mises stress (b): contact stress (c): shear stress

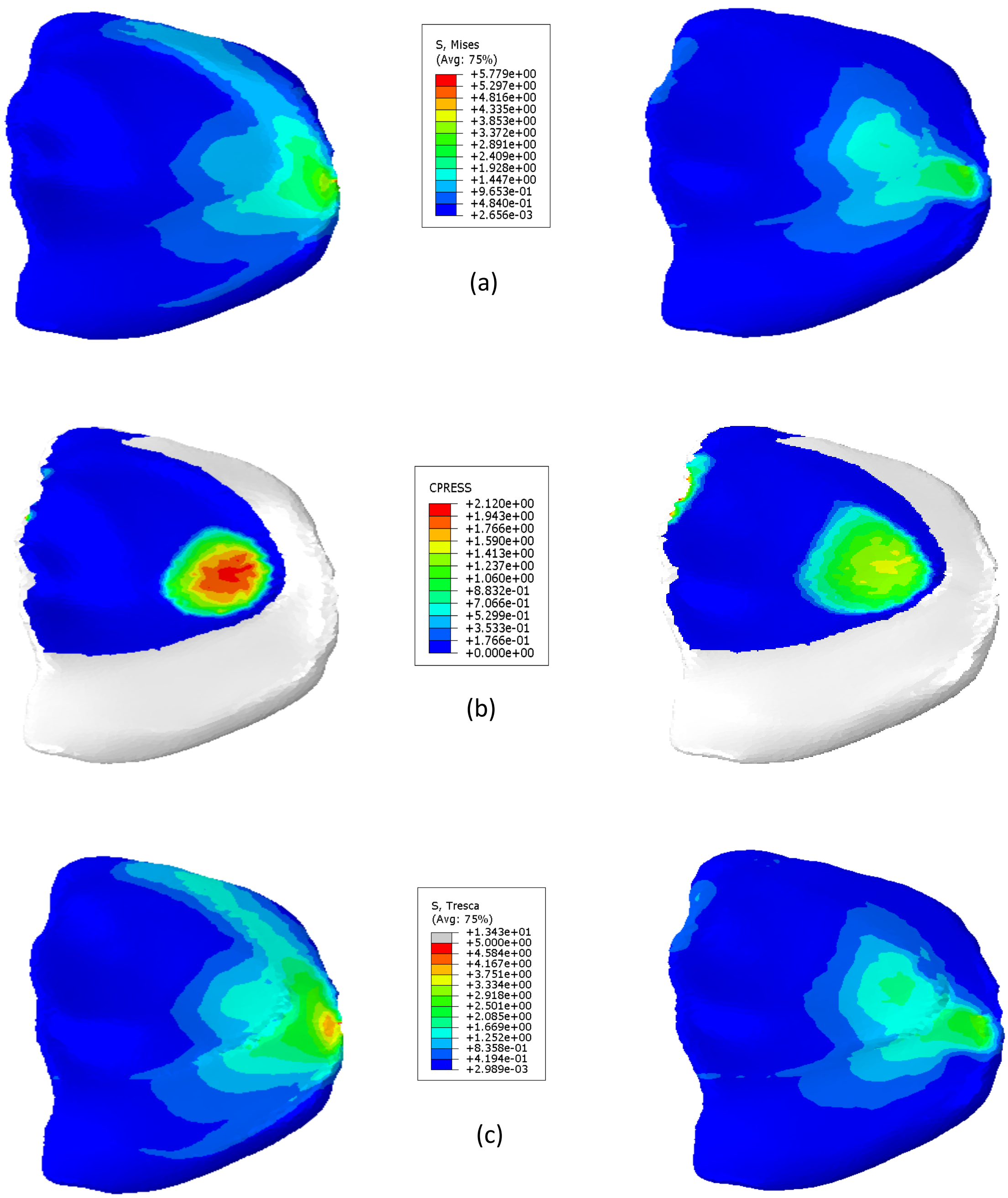



Fig33. Patient and post operation medial tibial cartilage indexes comparison (a): Von Mises stress (b): contact stress (c): shear stress

### 4.2.3 Effect of correction angle on the Mises stress distribution at tibial cartilage

The results obtained according to the different HKA angles after surgery are shown in Fig.34 and Fig.35. After HTO surgery, the HKA angle became -3°, -2°, and -1° was an undercorrection. After HTO operation, when the HKA angle is -3°, the Von Mises stress of the medial tibial cartilage is reduced by 25.9% to 4.28 MPa and the Von Mises stress of the lateral tibial cartilage is increased by 4.8% to 1.912 MPa. After the HTO operation, the HKA angle is -2° The Von Mises stress of the medial tibial cartilage was reduced by 32.6% to 3.893 MPa, and the Von Mises stress of the lateral tibial cartilage was reduced by 1.9% to 1.792 MPa, After HTO surgery, the Von Mises stress of the medial tibial cartilage was reduced by 37.9% to 3.586 MPa. The Von Mises stress of the lateral tibial cartilage increased by 4.5% to 1.793 MPa. After HTO surgery, the HKA angle became 3°, 2°, and 1° was an overcorrection. After HTO surgery, the HKA angle was 3° medially. The Von Mises stress of the tibial cartilage was reduced by 38% to 3.568 MPa, and the Von Mises stress of the lateral tibial cartilage was increased by 15% to 2.101 MPa. When the HKA angle is 2° Von Mises stress of the medial tibial cartilage was reduced by 41.2% to 3.397MPa. The Von Mises stress of the lateral tibial cartilage increased by 45% to 2.65MPa. When the HKA angle is 1° Von Mises stress of the medial tibial cartilage was reduced by 39.9% to 3.475MPa. The Von Mises stress of the lateral tibial cartilage increased by 23.4% to 2.385MPa.

After HTO surgery, under different HKA angles, the stress values of the lateral and medial compartments are different. undercorrection and overcorrection at a slight angle change can optimize surgery. Therefore, according to different HTO surgery situations, the correction angle of HTO surgery can be optimized better.

After HTO surgery, the stressing tendency of overcorrection (HKA angle more than zero degrees, lower limb is in valgus alignment) and undercorrection (HKA angle less than zero degrees, lower limb is in varus alignment) of medial and lateral tibial cartilage is shown in Fig. 33. The preoperative HKA angle was minus 7°, and the medial compartment stress was the most significant. With correction of the lower limbs after surgery, correcting the HKA angle to undercorrection, the medial compartment stress decreases as the correction angle increases. Finally, when the correction reaches 1° varus the medial compartment stress was lowest, with minor changes to lateral compartment stress level. Upon correcting the HKA angle to the neutral position, the stress of the medial compartment was higher than those observed at overcorrection and undercorrection. Upon overcorrecting the HKA angle, the results of valgus 1° to 2° are the closest to that of normal people. When the correction reaches valgus 2°, the medial compartment was at the lowest stress, with negligible increases in lateral compartment pressures. Furthermore, the stresses on the lateral and medial compartments are more balanced at these angles.

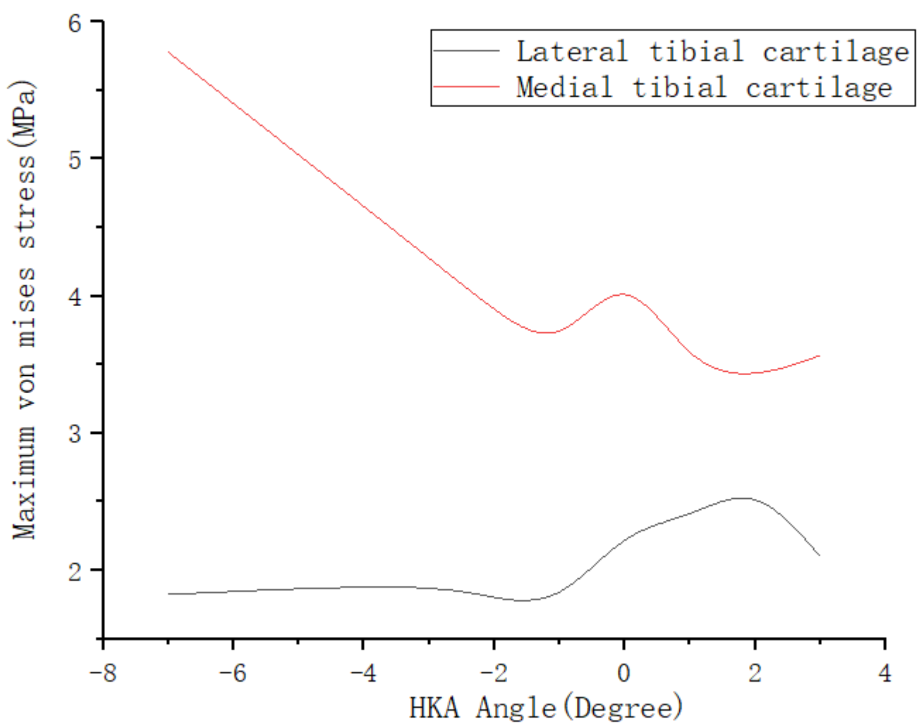
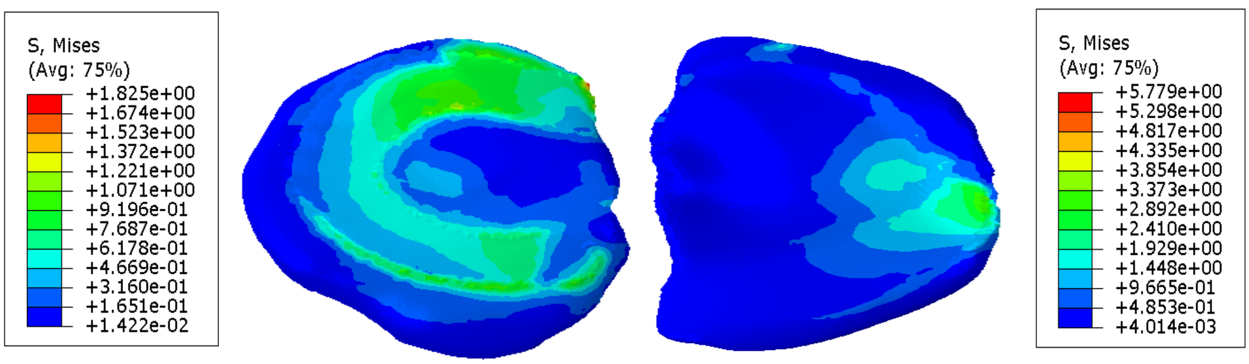
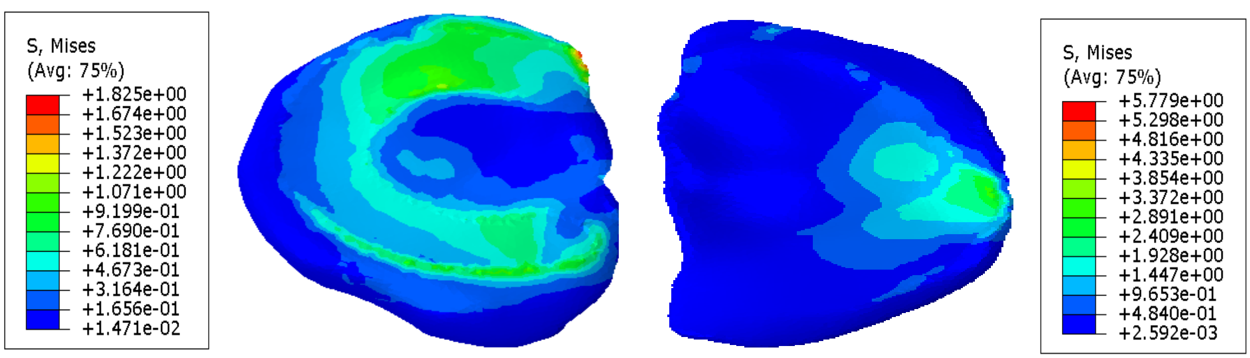


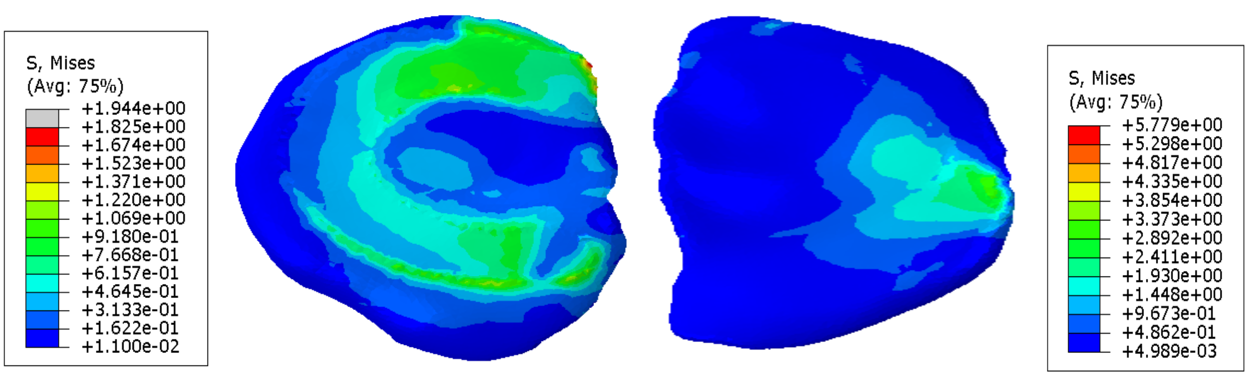

Fig34. The Von Mises stress of lateral cartilage (black) and medial cartilage (red) during high tibial osteotomy with HKA change




(a)




(b)




(c)

Fig35. The Von Mises stress on undercorrection tibial cartilage (a): HKA 3-degrees undercorrection knee (b): HKA 2-degrees undercorrection knee (c): HKA 1-degree

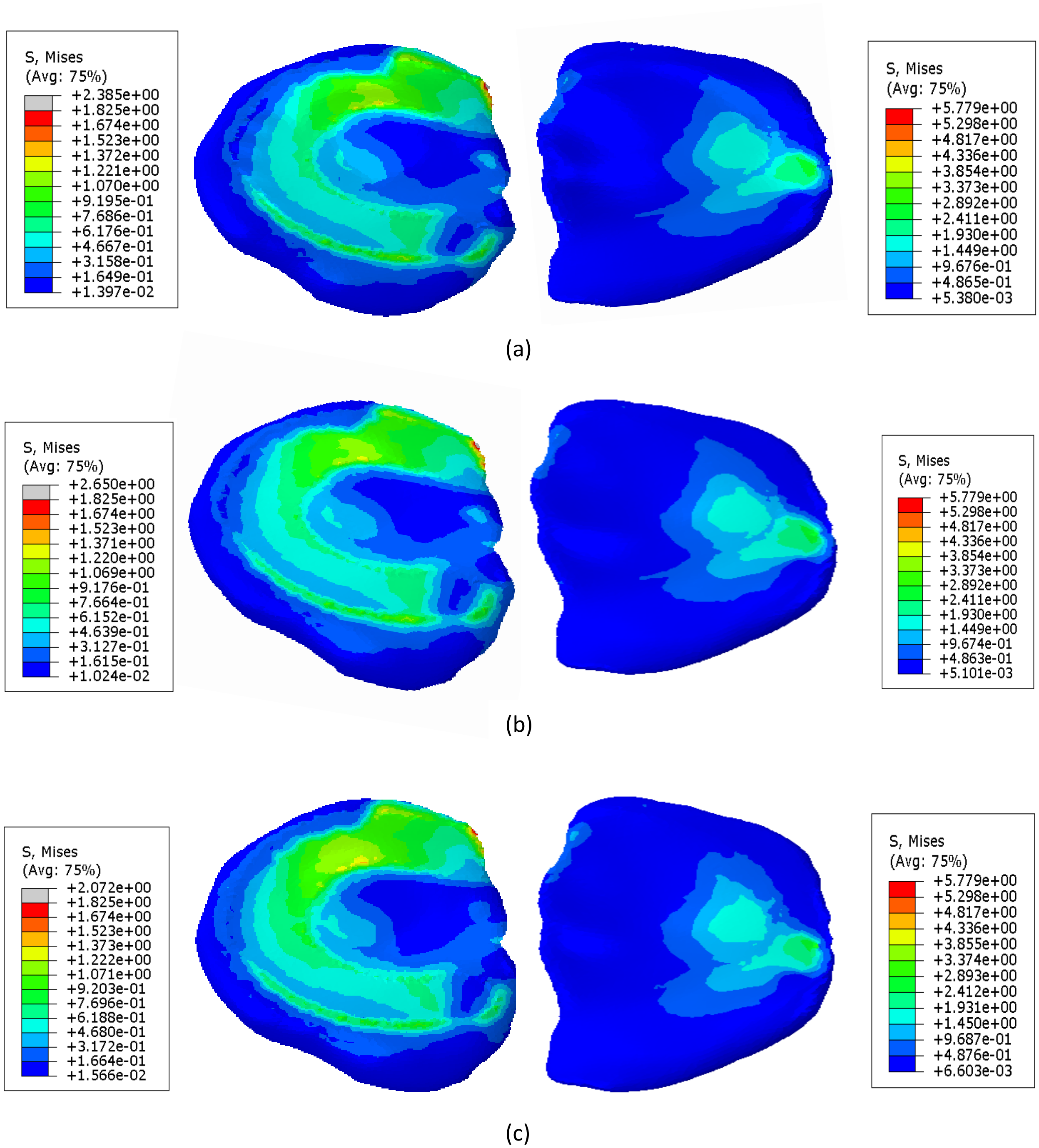



Fig36. The Von Mises stress on overcorrection tibial cartilage (a): HKA 3-degrees overcorrection knee (b): HKA 2-degrees correction knee (c): HKA 1-degree correction knee

## 4.3 Discussion

Appropriate and reasonable lower limb alignment is a factor that determines the success of HTO, however, it contains lack of consensus on ideal alignment. The HKA determines the load ratio of the lateral and medial compartments, with cartilage repair of the medial compartment and degeneration of the lateral compartment. [39] In the previous research, the moderately corrected knee after open wedge HTO had a better articular cartilage repair rate than the overcorrected knee. [40] However, the restoration of evenly distributed load on the two compartments of the knee joint in biomechanics may be ideal for HTO. [41] Ideally, an appropriate correction avoids overloading the lateral cartilage compartment while achieving the minimum overcorrection from baseline alignment required for adequate medial unloading. The most important finding of this study was that pressure in the medial compartment of both overcorrection and undercorrection lower extremities decreased with the change in the angle of HKA. However, the reduction in medial compartment pressure was limited when the lower limb was remaining in varus (in agreement with reference [42]). In contrast, remaining in near valgus 2°, the medial pressure drops to a minimum, and the medial and lateral pressures are relatively balanced. Our results are consistent with the hypothesis and other research results. [43] Patients with excessive loading of the lateral compartment after HTO are prone to damage to the lateral joint tissue. [44] There is little change in the lateral cartilage when the lower limb is undercorrected. However, in the overcorrection of the lower limb, the lateral cartilage forces increase slightly but are much less than the regular lateral cartilage forces [45]. Therefore, it is not believed that overcorrection in this study caused damage to the lateral cartilage. The innovation of this study is the construction of a complete lower extremity model, which was simulated with postoperative undercorrection and overcorrection of the lower limb. The relationship between the HKA and the medial and lateral compartment forces was investigated biomechanically under the premise that only the HKA was changed [46]. The medial and lateral compartment pressure results under static stance simulation were compared with previous studies, and the finite element stress results were generally consistent. The limitation of this paper is that our model uses simple material behavior to examine the stresses applied rather than actual values and simplified the details of the knee model and HTO details. The effect of excess ligaments and muscles is ignored. The actual surgical situation and the knee structure are more complex than the experimental procedure, so more clinical trials are needed to investigate the correction angle effect.

# Chapter 5 Conclusions and future work

## 5.1 Conclusion

In this study a validated intact lower extremity mode of a human body was developed. This model can be used to qualify the stress distribution of varus deformity. By comparing the stress distribution between the varus knee and normal knee, based on the results, we believe that HTO can product good effect for OA.

The completed lower extremity model simulates postoperative undercorrection or overcorrection of the lower limb. The relationship between the HKA and the medial and lateral compartment forces was investigated biomechanically under the premise that only the HKA was changed. The medial and lateral compartment pressure results under static stance simulation were compared with previous studies, and the finite element stress results generally were consistent.

By simulating overcorrection and undercorrection lower limb finite element models it was found that the best surgical results are obtained in the undercorrection of the lower limb when remaining to 1° varus. On the other hand, the best results are achieved when the correction is 2° valgus at the overcorrection. Furthermore, the surgical result of overcorrection is better than that of undercorrection.

## 5.2 Future work

In this study we acknowledged several limitations, including use of models of simple material behavior to examine the stresses applied rather than actual values and simplification of the details of the knee model and HTO. Moreover, the effects of excess ligaments and muscles are ignored. Finally, as the actual surgical situation and knee structure are more complex than in the experimental procedure, clinical trials are needed to investigate the correction angle.

In the future, we will overcome all the limitation to achieve better results.

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