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Investigation of Stress Distribution in Healthy and Arthritic Knee Joints After Registering 3D Files on the Radiographic Images

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Abstract
Knee arthritis is a prevalent health issue; most knee surgeries are performed for this condition. It primarily affects older people, progresses slowly, and impacts various components of the knee joint. Due to the destruction of articular cartilage in the knee over time, investigating joint destruction based on applied stresses is crucial. This study utilized CT scans and MRI images with the Mimix software to extract 3D knee joint models. A dedicated software developed in the MATLAB GUI environment was used to match 3D CT scan files with radiographic images. The final 3D knee joint model was created using Solidworks software. Numerical simulations were then conducted using Abaqus software to calculate cartilage stresses in healthy and arthritic knees. The study found that the amount of stress in the middle side of the knee joint was consistently higher than on the lateral side. This difference was greater in arthritic joints than in healthy ones, highlighting the importance of understanding stress distribution in the knee joint and its impact on arthritis progression. The study methodology can help improve knee arthritis treatment strategies, as it allows for the development of more accurate 3D models and simulations to understand joint mechanics better.

Keywords: Knee Joint, Arthritis, Stress Distribution, Finite Element, Cartilage.

1. Introduction

The knee is the largest joint in the human body, capable of bearing the entire weight of the body while standing and even more weight during activities such as walking or running. As a result, knee problems are among the most common ailments affecting individuals of all ages, particularly the elderly [1]. The knee joint is where the femur and tibia bones come together, and it consists of three primary bones: the femur, tibia, and patella. The medial and lateral meniscus are located between the surfaces of the femur and tibia. Arthritis is a joint disease that progresses slowly, causes pain, and restricts movement. It affects components of the knee joint, such as the articular cartilage. Structural changes in joint components and secondary inflammation contribute to the clinical symptoms of this disease.

In advanced cases, arthritis can result in the complete destruction and failure of the joint. Recent research suggests that arthritis may originate from the outer surface of the cartilage due to increased tension in this area [2]. Given its significance, knee arthritis has been extensively studied by researchers from various disciplines. Mechanical investigations and the impact of forces on the knee joint have been the focus of many studies. Currently, studies that model the knee joint primarily focus on the behavior of cartilage, meniscus, and ligaments. It is not always necessary to model all components of the knee joint for numerical simulations. The selection of components to include in the model depends on the specific loading and sensitivity of the subject being studied.

2. Methodology

In studies that primarily focus on cartilage behavior or investigate arthritis, ligaments are often not explicitly modeled and are instead replaced with boundary conditions or represented by linear springs [3-6]. The simulation of textures is generally not feasible through geometric modeling, and their effects are typically incorporated into boundary conditions [7].

For this study, two knee joints were selected: a healthy joint from a 61-year-old woman and an arthritic joint from a 67-year-old man. Radiographic, CT scan, and MRI images were available for both joints. The Mimics software was used to extract 3D models of the bones from the CT scan images. The software also provided initial 3D shapes for the meniscus and cartilage using the MRI images.

After segmenting the various components of the knee joint, particularly the femur and tibia bones, 3D models consisting of cloud points were created for each component and saved in the STL format. To perform finite element calculations, a 3D model of the knee joint in a loaded state was required. However, during the CT scan imaging, the patient was lying down and the knee joint was not under load. In contrast, during X-ray imaging, the patient was standing, and the joint was under load. To obtain a loaded knee joint, the CT scan images were superimposed onto 2D radiographs of the joint in a loaded state, and the bone positions were adjusted until they matched the radiographic images.

A MATLAB-based graphical user interface (GUI) was developed for this purpose, which allowed the 3D models of the femur and tibia in STL format to be uploaded onto the 2D radiographic images. Figure 1 provides an illustration of this process.

Figure 1: Displaying the boundaries of the STL files for the bones within the generated GUI environment.

To create the final shape of the knee joint, all components were imported into SolidWorks software. However, since this software cannot directly work with STL files, Geomagic software was used to convert the STL point cloud files into surface files in the STP format. The resulting 3D files were then imported into 3-matic software, where meshing was performed using four-node tetrahedral elements (C3D4) [8, 9]. To determine the optimal mesh size, a mesh convergence analysis was conducted by gradually increasing the mesh density until the maximum deviations in the computed stresses were less than 5%. The resulting number of elements was 495,655 for the healthy joint and 463,695 for the arthritic joint. After meshing and running an element sensitivity analysis, the final model of the healthy joint was prepared for numerical simulation, as shown in Figure 2.

In this study, all joint components were assumed to be isotropic linear elastic materials [10], with Young's moduli of 18600, 12500, 12, and 59 MPa and Poisson's ratios of 0.3, 0.3, 0.49, and 0.49 for the femur, tibia, cartilage, and meniscus, respectively.

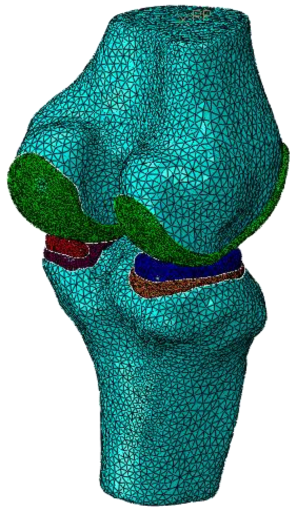


Figure 2: The final model of the healthy joint prepared for analysis.

The contact direction between the components was defined as hard contact in the vertical direction and without friction in the tangential direction. The surface-to-surface contact option in Abaqus software was used to define the contact between femoral cartilage and meniscus, between femoral cartilage and tibial cartilage, and between tibial cartilage and meniscus.

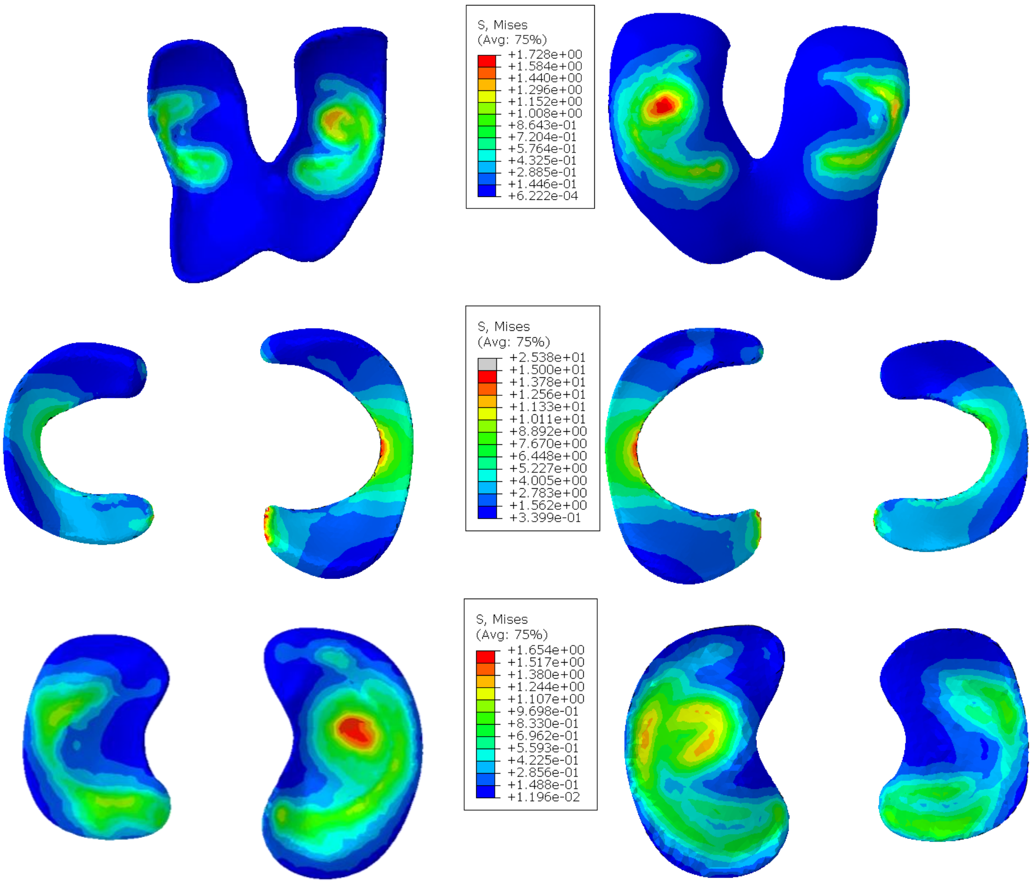
The horns of the meniscus were connected to the tibia using five springs with a stiffness of 200 N/mm in each horn. Additionally, to prevent movement of the cartilage relative to the bones, the femoral cartilage was attached to the femur bone, and the tibial cartilage was completely attached to the tibia bone and fixed [11, 12].

The lower surface of the tibia bone was completely fixed in all three directions and had no rotation or displacement. A concentrated load of 800 N was applied to a reference point located on the upper surface of the femur in the z-direction. This reference point was coupled to the upper surface of the femur, and movement along the z-axis was open while other movements were completely constrained.

The simulation was conducted using Abaqus software version 2021 on a 7-core system, with 4 cores used for solving. The simulation took approximately 12 hours to complete, with a time step size of one second and explicit dynamic type. To speed up the simulation and reduce solution time, a mass scale size of 10000 was used, and at the end of the solution, the kinetic energy was checked to ensure it did not exceed 7% of the internal energy.

3. Discussion and Results

The von Mises stress distribution in the femur, tibia cartilages, and meniscus of a healthy joint was obtained according to Figure 3**:**.



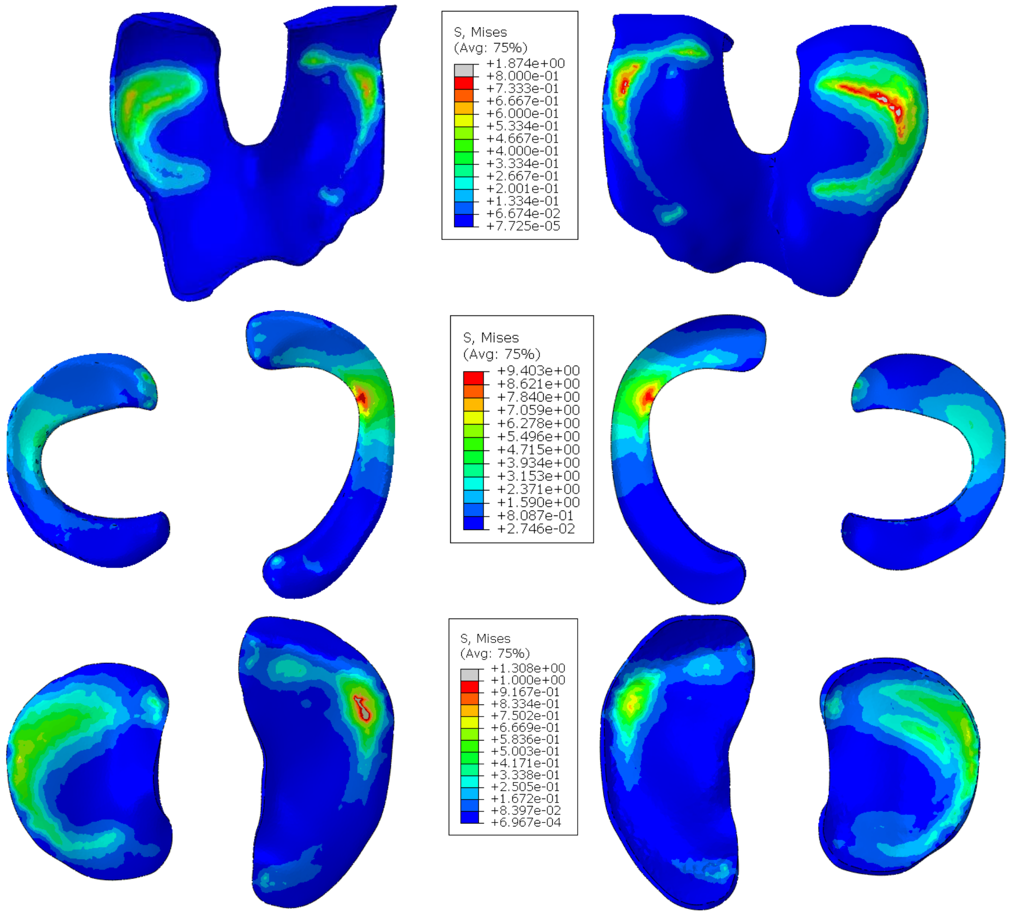
Lateral Medial Lateral

Figure 3: The von Mises stress in the cartilages and meniscus of a healthy joint was visualized from a lower (right) and upper (left) view.

In a healthy joint, the maximum stress in the femoral cartilage was found to be 1.73 MPa, while in the tibial cartilage it was 1.65 MPa. These results indicate that some of the force has been absorbed by the meniscus, demonstrating their effect on stress distribution and shock absorption during loading. The maximum stress on the femoral cartilage was calculated as 1.73 MPa on the medial side and 1.42 MPa on the lateral side, while on the tibial cartilage, it was 1.65 MPa and 1.11 MPa on the medial and lateral sides, respectively.

These findings are consistent with previous studies that have observed greater stress on the central cartilages compared to the lateral cartilages in the joint structure. The point of contact between the femoral and tibial cartilages was found to be the location of maximum stress.

The stress distribution in the cartilages and meniscus of the arthritic knee joint is presented in Figure 4:. In an arthritic joint, stress is not uniformly distributed and is mostly localized on the cartilage. The maximum stress in the femoral cartilage was found to be 1.87 MPa in the central region and 0.88 MPa in the lateral region, while in the tibial cartilage, the maximum stress was reported as 1.31 MPa and 0.84 MPa for the medial and lateral sides, respectively. These results suggest that arthritis progresses from the central region of the joint, where the maximum stress is observed.



Lateral Medial Lateral

Figure 4: The von Mises stress in the cartilages and meniscus of an arthritic joint was visualized from a lower (right) and upper (left) view.

4. Conclusions

This study aimed to investigate the distribution of stress in the cartilages and meniscus of healthy and arthritic knee joints. The results demonstrated that the middle cartilages in both healthy and arthritic joints experienced higher stresses than the lateral side. Moreover, the femur cartilage always experienced higher stress than the tibial cartilage, which represents the presence of the meniscus. These findings confirmed that arthritis typically begins from the middle side of the joint, and the presence of arthritis increased the medial-to-lateral stress ratio, exacerbating disease progression. Specifically, the study found that the stress on the medial side of the femoral cartilage was 22% higher than that on the lateral side in the healthy joint, but this difference increased to 112% in the arthritic joint. Similarly, for the tibial cartilage, the percent difference was 49% in the healthy joint and 56% in the arthritic joint.
The study also demonstrated that modeling all components of the knee joint for numerical simulations is not always necessary, and the selection of components to include in the model depends on the subject's specific loading and sensitivity. The theoretical and practical implications of this study can help improve treatment strategies for knee arthritis by directing attention to the central region of the joint. The findings can inform the development of novel therapies and surgical interventions that target the central region of the joint, ultimately improving outcomes for patients.
Finally, the study highlights the importance of using advanced imaging and simulation techniques to better understand knee joint mechanics and develop more effective treatments for knee arthritis. Overall, these findings contribute to the growing body of knowledge on knee joint mechanics and have significant implications for the development of improved treatment strategies for knee arthritis.

5. References

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