

Finite Element Analysis of the Open Wedge Osteotomy Technique in Proximal Tibia Bone

Abstract

Background and Objective: Deviation in the healthy alignment of bones is a common issue among orthopedic patients. One specific manifestation of these deformities in the knee is seen as genu varum (bow-legged) and genu valgum (knock-kneed). There are relatively clear indications for correcting these issues, typically performed through surgical osteotomy, reshaping the bone, and fixing it in a new position. Various techniques exist in this field, including different surgical approaches, types of osteotomy, and fixation devices. The aim of this study was to perform a finite element analysis and biomechanical comparison of the open wedge osteotomy technique in the proximal tibia bone. This involved simulating the impact of osteotomy surgery on the correction of lower limb alignment. The biomechanical behavior of four conditions was examined: the plate profile being either curved or straight and the proximal screw orientation being either convergent or divergent under static load on the finite element model. Additionally, to better reflect reality, one of these four conditions was modeled with threaded orthopedic screws.

Methods: To ensure the modeling and simulation were as close as possible to the references, CT scan images of a bone mold provided by the project consultant were used, comprising 379 slices. The CT scan images were transferred to Mimics software. The geometric configuration of implants and orthopedic screws was drawn in SolidWorks software after their physical preparation. Subsequently, the model underwent biomechanical analysis in a static mode using Abaqus software (version 6.14.2). To achieve a realistic model in terms of properties, cortical bone was considered orthotropic, cancellous bone was considered planar isotropic, and the implants and orthopedic screws were made of titanium alloy.

Results: In comparing von Mises stress among the four scenarios, the curved plate with convergent proximal screw direction exhibited the highest von Mises stress on the implant and orthopedic screws. However, the von Mises stress on the bone in this scenario was the lowest compared to other scenarios, with the highest likelihood of stress shielding occurrence. In contrast, the flat plate with divergent screw direction had the lowest von Mises stress on the implant and orthopedic screws, which is expected to have the best biomechanical properties. When threading was considered for the orthopedic screws in the modeling, stress significantly increased on the bone, implant, and orthopedic screws. This indicates the importance and necessity of considering the threading of orthopedic screws in finite element modeling, as removing the threading would eliminate the stress concentration on the screw threads, leading to results that differ from reality.

Keywords: osteotomy, tibia, finite element analysis, Genu Varum, Genu Valgum

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Introduction

One of the main reasons for arthritis and knee joint degradation starting from a young age is the misalignment of the bones around the knee. This misalignment causes excessive pressure on either the inner or outer sides of the knee, as the weight axis of the limb passes through one side of the knee instead of its center. The most significant deformities manifest as "bowlegs" or "knock-knees" (Figure 1). Osteotomy is a surgical procedure where the tibia bone is precisely cut by the surgeon using special tools and then realigned. The bone is fixed in place with screws, plates, external fixators, or casts to heal in the correct position⁽¹⁻⁶⁾.

Generally, there are two osteotomy methods: 1) Open wedge, 2) Closed wedge (Figure 2)(6-8). Powerful methods that have been used for the past two decades to analyze physical phenomena include the Finite Element (FE) method and the Boundary Element (BE) technique. In recent years, significant advancements have

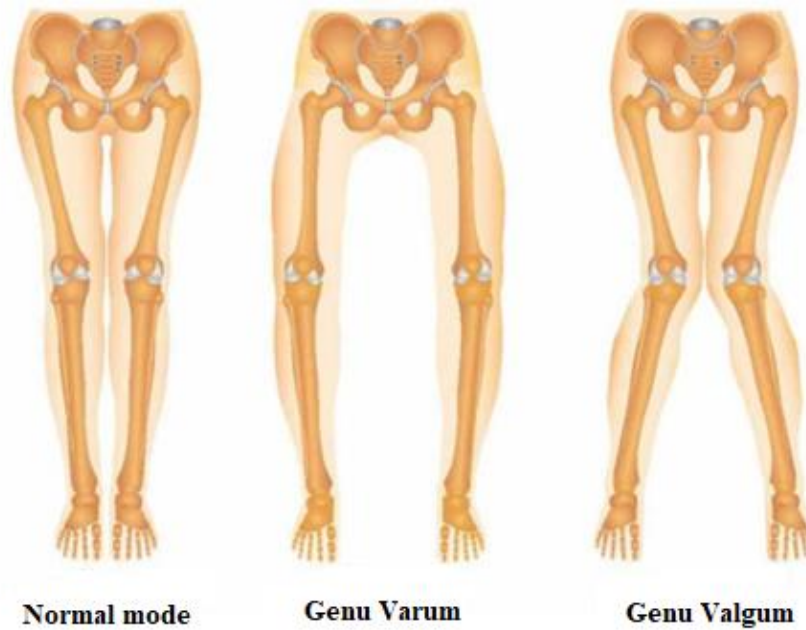


Figure 1 - From right to left: Crossed knee, bow-legged knee, normal knee

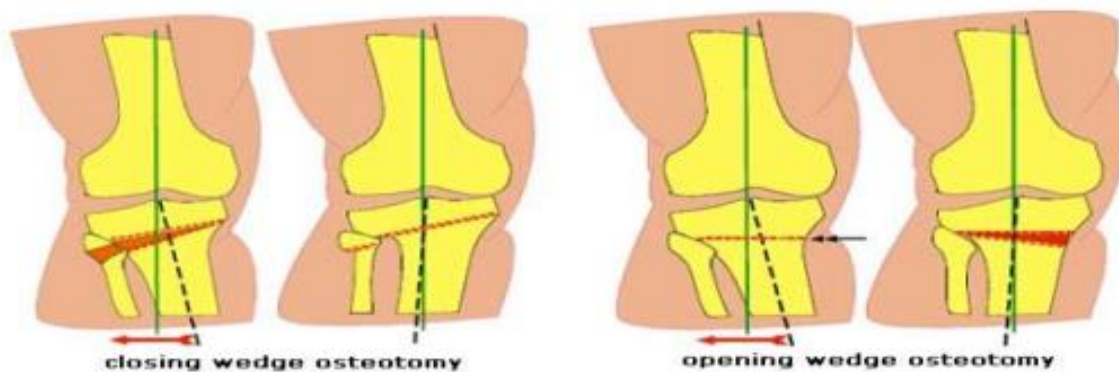


Figure 2 - Right: Open wedge, Left: Closed wedge⁽⁷⁾

been made in the application of finite element methods in the field of biomechanics. Research on the application of these numerical methods covers areas such as the analysis of biological flows, soft tissue mechanics, orthopedic mechanics, and more^(2,3).

Materials and Methods

In this study, modeling and simulation were carried out as closely as possible to the actual anatomy of the leg. This has always been a point of focus for biomechanics researchers. Using bone molds similar to reference samples used in the cited articles, which were prepared by the project consultant, the initial model, including bone tissue based on CT scan

images in 379 slices at 1.5 mm intervals stored in DCM format, was developed in Mimics software (version research20.0). The model was then transferred to 3matic software (version research 12.0) for refinement⁽¹⁰⁾.

Various orthopedic plates such as Tomo fix, pudu, and flexit are used for osteotomy⁽⁴⁻⁸⁾. The geometric shape of the plates and orthopedic screws was designed using the catalog from the Synthes company. Additionally, two types of curved and straight plates, plus eight screws for implants, including three types of 6.5 mm cancellous screws, 6.5 mm and 8 mm lag screws, and threaded screws for implants, were designed in Solid Work software (version 2017)⁽¹⁰⁻¹³⁾.

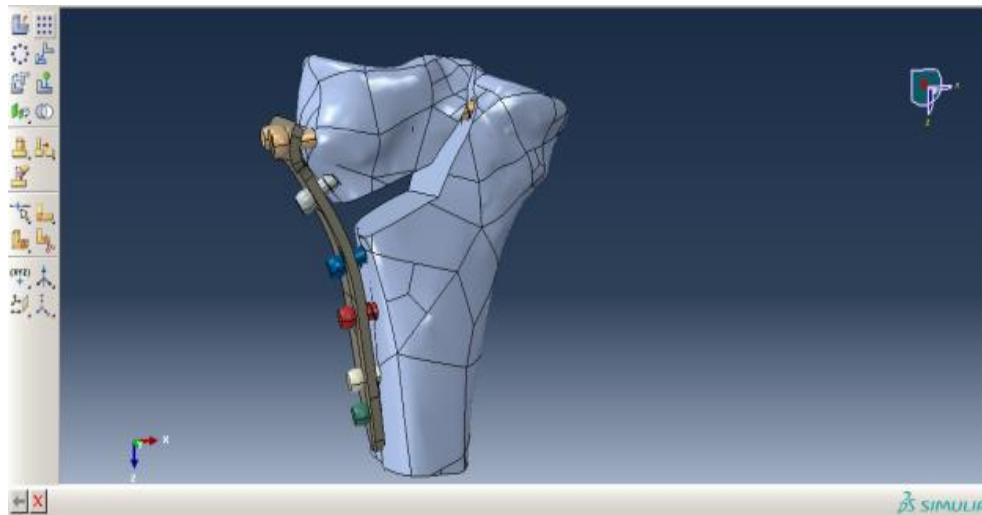


Figure 3 - Assembled model including the bone, implant, and threaded screws.

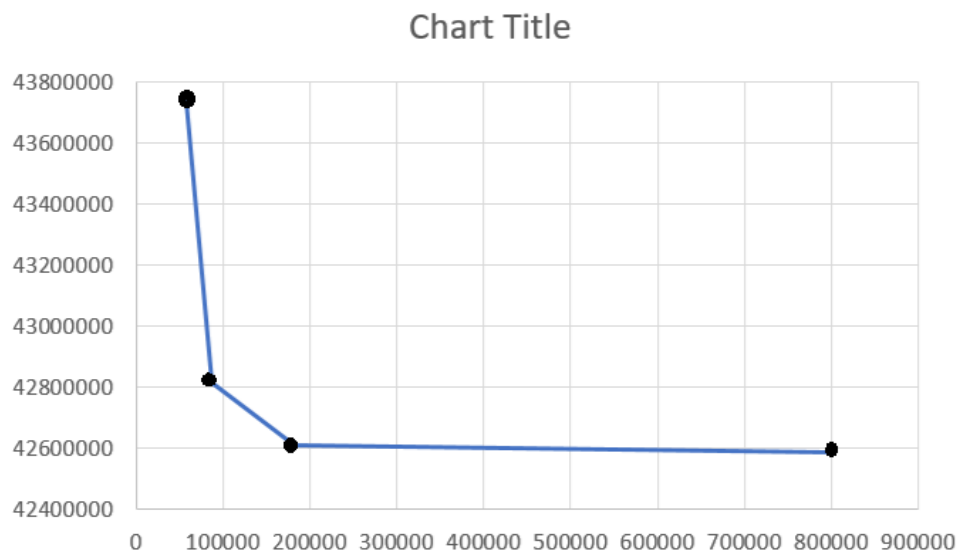


Figure 4 - Chart showing convergence of responses based on the maximum stress index in the bone with increasing number of elements.

To complete the processes related to the present study, the mentioned model was transferred to mechanical modeling and simulation software. For this purpose, the Abaqus software package (Abaqus/CAE6.14.2) was used in this research.

In the present study, four osteotomy models were simulated, including two plate profiles, one curved and one flat, with proximal screws oriented as either convergent or divergent. Additionally, three models used the technique of inserting opposing screws with three types of screws: 5/6 mm cancellous screws, 5/6 mm cortical screws, and 8 mm lag screws (Figure 3)⁽¹⁴⁾.

To enhance calculation accuracy, the mechanical properties for cortical bone were considered orthotropic and anisotropic, while for spongy bone, they were considered isotropic and planar.

The elastic modulus and Poisson's ratio for the implant and orthopedic screws were set at 105 GPa and 0.3, respectively. In this study, the bone was fixed to the ground 4 mm below the plate area and considered fixed in all degrees of freedom. According to reference articles, a load of 2450 Newtons was applied, simulating the maximum compressive load on the knee for a person weighing 70 kg, which is equivalent to three times this weight.

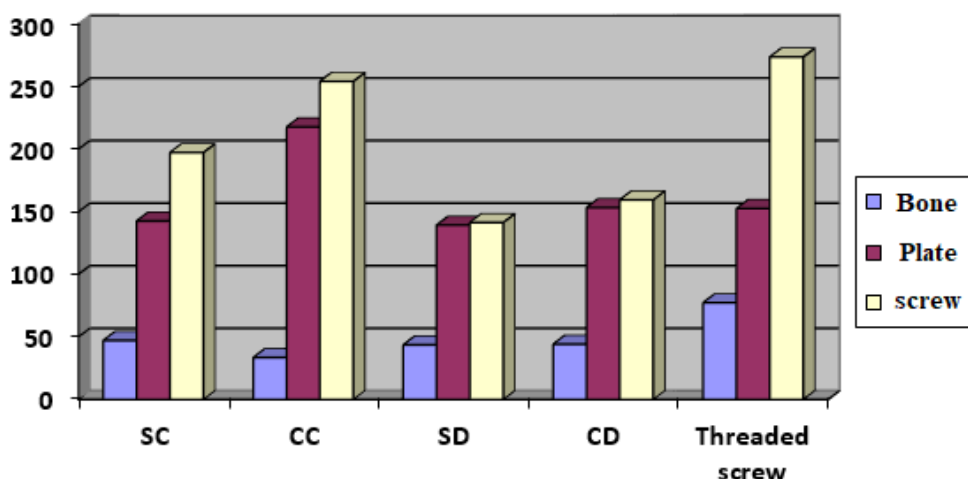


Figure 5 - Bar chart of maximum von Mises stress in the bone, implant, and screws in the five modeling cases.

Table 1 - Numerical values of von Mises stress index in the bone with varying numbers of elements.				
Mesh size	4 mm	3 mm	2 mm	1 mm
Number of elements	57854	87627	181910	801090
Number of nodes	11260	16897	34480	153169
Stress	43735613	42816413	42609267	42589355

This load was distributed with 60% (1470 Newtons) applied medially and 40% (980 Newtons) laterally⁽¹⁰⁾. Additionally, to simulate the load from body weight on the tibia of a person weighing 60 kg, a load of 600 Newtons (equivalent to the loading from the person's weight) was applied to the entire tibia⁽¹⁵⁻¹⁸⁾.

Results

ANALYSIS OF THE INDEPENDENCE OF RESPONSES FROM THE NETWORK:

In the first phase, to ensure the independence of the responses obtained from the numerical solution, the size and consequently the number of elements used in the numerical solution were examined through several stages (Figure 4 and Table 1).

The maximum von Mises stress on the screw and plate occurred with the plate in the bent condition and the screw in the convergent direction (CC), while the maximum von Mises stress on the bone occurred with the plate in the flat condition and the screw in the convergent direction (SC). Additionally,

taking into account the threads of orthopedic screws in the von Mises stress modeling, the stress reached its maximum on the screw, plate, and bone, indicating the importance of screw threads in finite element modeling. Meanwhile, von Mises stress is a result of various loads applied to a region, and its magnitude is calculated by the software (Figure 5).

The maximum deformation of the screw and bone occurred with the plate in the bent condition and the screw in the convergent direction (CC), while the maximum deformation of the implant occurred with the plate in the bent condition and the screw in the divergent direction (CD) (Figure 6). Regarding the opposing screw insertion technique, the maximum von Mises stress on the implant occurred with the 6.5 mm cancellous screw insertion technique (Figure 7).

Discussion

In this study, the effects of screw orientation and the profile of orthopedic plates on the risk of failure

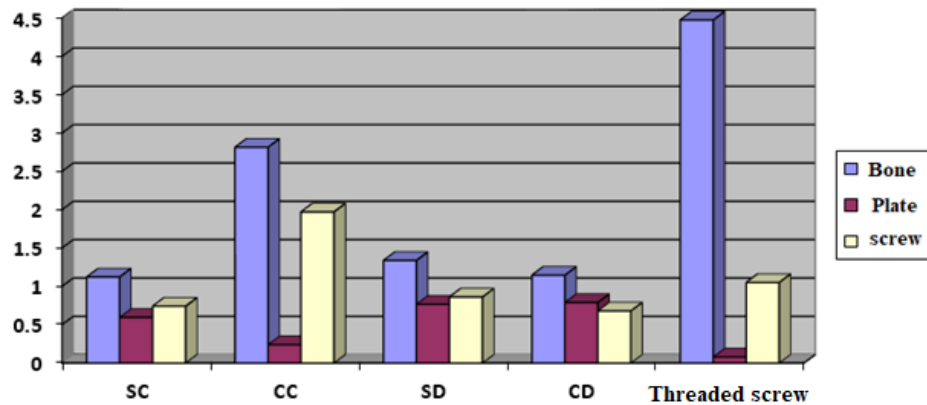


Figure 6 - Bar chart of deformation in millimeters for the five modeling cases.

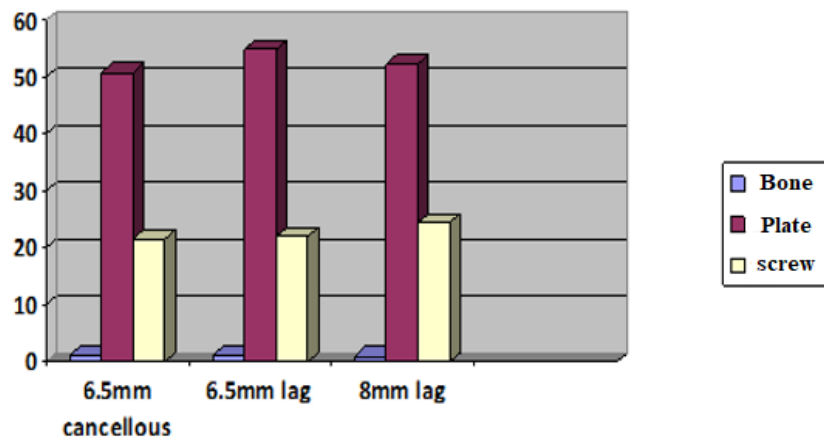


Figure 7 - Chart of von Mises stress for the opposing screw insertion technique.

and structural stability were examined using finite element analysis. The analysis focused on the stress and deformation patterns, including maximum values and indices. From a biomechanical perspective, changes in von Mises stress are significant indicators of mechanical performance. Based on the results of this study, the maximum stress in the bone for the anisotropic case was 15.47 MPa (SC state) (Figure 8), the maximum von Mises stress for the implant was 8.217 MPa, and for the orthopedic screws, it was 2.254 MPa (CC state).

In contrast, the aforementioned values in the isotropic case were 6.42 MPa for the bone, 213 MPa for the implant, and 259 MPa for the orthopedic screws, with these differences attributed to the application of anisotropic properties in the finite element modeling.

Regarding deformation, the maximum deformation in the bone under the anisotropic condition was about 15% less compared to the isotropic condition (CC state). According to the results from the current

finite element modeling project, it can be concluded that a curved plate and converging screw orientation result in the highest von Mises stress on the implant and orthopedic screws and the lowest von Mises stress on the tibia bone (52.33 MPa). Therefore, the implant bears a greater load, and the likelihood of stress shielding phenomena in this case is also very high. In the current study, a divergent screw orientation with a curved implant (CD) with threaded screws was also simulated. The maximum von Mises stress for the bone increased from 43.62 MPa to 77.26 MPa. Additionally, the maximum von Mises stress on the implant and screws decreased from 153.3 MPa to 152.6 MPa and increased from 195 MPa to 273.7 MPa, respectively. This difference indicates the necessity of considering screw threading in finite element modeling, as omitting screw threads can lead to inaccurate stress concentration results.

Figure 9 shows the von Mises stress for the curved plate with a divergent screw orientation, both with

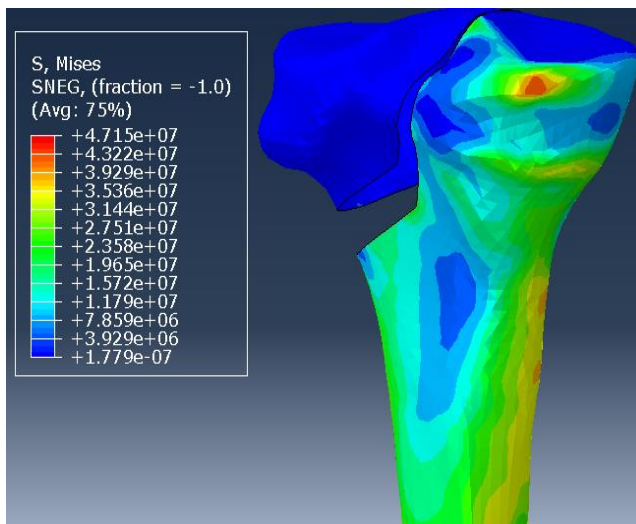


Figure 8 - Maximum von Mises stress in the flat plate with converging screw orientation (SC).

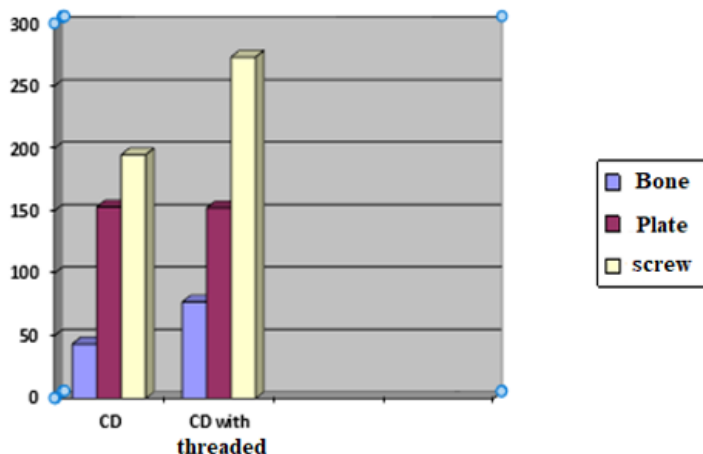


Figure 9 - von Mises stress for the curved plate with divergent screw orientation, both with and without threading.

and without threading. Accordingly, the maximum von Mises stress for the bone without threading was 44.14 MPa, and this value increased to 77.26 MPa when considering screw threads.

The divergent screw orientation can reduce the risk of failure for all components and provide better structural stability, whereas a curved plate profile seems to have adverse effects. Conversely, the stress shielding phenomenon is least likely in the flat plate with a divergent screw orientation (SD) compared to other states. Ultimately, if structural stability is the main concern, the flat plate with a divergent screw orientation (SD) is recommended for heavy patients and those with a larger proximal tibia. For slender and lightweight patients, a curved plate might be more suitable to avoid soft tissue irritation. Regarding the opposing screw technique,

the maximum von Mises stress for the 6.5 mm cancellous screw on the screw and implant was lower than in the other two cases. Therefore, the likelihood of stress shielding is lower in this technique compared to the others, suggesting it has the best biomechanical properties.

Conflict of Interest

This review was conducted without any financial assistance or personal and commercial relationships, adhering to academic integrity and ethical behavior principles. This review is based on the master's thesis of Abolfazl Majidi Yazdi, one of the researchers involved in this study.

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