Finite element analysis of intramedullary nailing and nail-plate combinations for treating unstable proximal tibial metaphyseal fractures

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ABSTRACT

BACKGROUND: The anatomy of the proximal tibia presents treatment challenges, and there is currently no widely accepted surgical fixation method for fractures in this region. The aim of this study is to evaluate the efficacy, benefits, and differences between intramedullary nailing (IMN) with a 4-hole Limited Contact Dynamic Compression Plate (LC-DCP) combination and IMN with an 8-hole LC-DCP combination in unstable fractures of the proximal metaphyseal region of the tibia.

METHODS: An oblique fracture was created in the metaphyseal region, forming a 30-degree angle in the sagittal plane in three tibial models. The fracture was designed to be 5 cm distal to the knee joint anteriorly and 8 cm distal to the knee joint posteriorly. One model was fixed with intramedullary nailing alone, while the others received additional fixation with either a 4-hole or an 8-hole plate in addition to the nail. Finite element analysis was performed using 3D computed tomography images of the models. Deformation, displacement, von Mises stress, and maximum principal strain values resulting from axial, lateral, coronal, and rotational forces applied to the models were analyzed.

RESULTS: The model fixed with intramedullary nailing alone demonstrated greater maximum stress, maximum deformation, and displacement under all applied forces. In the model with nail and 8-hole plate, unlike the other models, the highest amount of stress in the nail was concentrated on the distal locking screw under axial force. We observed that the maximum principal strain in the tibia was higher in the models with combined nail and plate fixation than in the model with intramedullary nailing alone.

CONCLUSION: The results of this study indicate that the combination treatment with an 8-hole DCP plate is biomechanically superior for treating unstable proximal tibial fractures with nails. Although the nail-plate combination requires an additional surgical incision and extra implants, it provides advantages in terms of stability and the sustainability of fracture reduction in unstable fractures.

Keywords: Biomechanics; finite element analysis; proximal tibial fractures.

INTRODUCTION

Tibial fractures are a common occurrence among long bone fractures. Extra-articular proximal tibial fractures account for approximately 5-11% of all tibial fractures.[1] Plate osteosynthesis, intramedullary nailing (IMN), and external fixation are all viable surgical options for treating proximal tibial fractures. However, due to the complex anatomy of the proximal tibia, there is no universally accepted treatment method.

The use of intramedullary nails by surgeons in the treatment

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of proximal tibial fractures is becoming increasingly common.[2] Fractures located in the proximal tibia treated with IMN exhibit a higher incidence of malalignment compared to mid-diaphyseal and distal fractures.[3] Awareness of complications associated with IMN has led to the development of specialized nailing techniques and reduction methods that minimize these complications.[4] Over the past 25 years, clinical research and the development of various implants have significantly improved outcomes following nailing of proximal metaphyseal tibial fractures. In addition to nailing, combinations with temporary or permanent implants such as Poller screws or plates have been used to prevent malalignment and instability.[5] The combination of nailing with plate can be employed to achieve reduction during surgery and maintain support afterward.[6] Nevertheless, a biomechanical analysis of the IMN-plate combination is necessary.

Finite element analysis (FEA) is commonly used in orthopedics for various purposes, including implant design, preoperative planning, nonunion detection, and surgeon training.[7] Moreover, FEA provides a standardized system for evaluating various clinical treatments, which reduces the time and cost associated with studies.[8] The aim of this study is to evaluate the efficacy, benefits, and differences between IMN with a 4-hole Limited Contact Dynamic Compression Plate (LC-DCP) combination and IMN with an 8-hole LC-DCP combination in unstable fractures of the proximal metaphyseal region of the tibia using FEA. Our hypothesis in designing this study was to prove that the combination of IMN and an 8-hole plate is biomechanically superior.

MATERIALS AND METHODS

Planning of Models

To create the fracture and place the implants, three third-generation composite synthetic tibias were used. The oblique fracture was designed to form a 30-degree angle, similar to the AO/Orthopaedic Trauma Association (AO/OTA) 41A2 fracture pattern.[9] The fracture was positioned 5 cm distal to the knee joint anteriorly and 8 cm distal to the knee joint posteriorly.

Model A was fixed solely with an 8 x 300 mm intramedullary nail, secured with two distal and four proximal locking screws. In model B, in addition to the nail, a 4.5 mm narrow 4-hole LC-DCP plate with two locking screws proximal to the fracture and two locking screws distal to the fracture was used. In model C, an 8-hole, 4.5 mm narrow LC-DCP plate was used in addition to the nail, with two locking screws proximal and two locking screws distal to the fracture.

Computed tomography (CT) images of the tibial models were obtained and saved in DICOM (Digital Imaging and Communications in Medicine) format. The DICOM data was transferred to MIMICS 10.01 software (Materialise, Leuven, Belgium). The MIMICS software determined the upper and lower Hounsfield Unit (HU) values to identify the bone structure and selected pixels on the CT image accordingly. This process, known as thresholding, allowed for the registration of the bony structures using a mask, and models were obtained through InVesalius 3.1 (Center for Information Technology Renato Archer, Campinas, SP, Brazil). The biomodels were imported into SolidWorks to create the 3D solid models, with the final models simulated using a 1 mm fracture gap (Fig. 1).

Finite Element Analysis

Finite element partitioning and meshing were performed on the obtained solid models using Ansys Workbench software (ANSYS Workbench, ANSYS Software Corporation, Canonsburg, USA). We used tetrahedral elements to mesh the geometries in this study (Fig. 2). The bone tissue was modeled using second-order tetrahedral elements with an edge length of 2 mm, while 1 mm second-order tetrahedral elements were used for the plate and nail geometries. The number of nodes and elements created for the three different models is shown in Table 1. Material properties were assigned to the 3D models based on information from the literature.[10] All material properties were assumed to be linear and isotropic (Table 2).

The contact properties between the screws and bone were defined as 'No Separation' in Ansys software. This contact feature is a pattern that maintains screw-bone tissue connection while allowing slight movement. The connection between the screws and the nail and plate was considered fully bonded. The contact properties of the intramedullary nails and plates with bone were considered frictional, with the coefficient of friction set at 0.23.

Figure 1. Final models prior to finite element analysis.

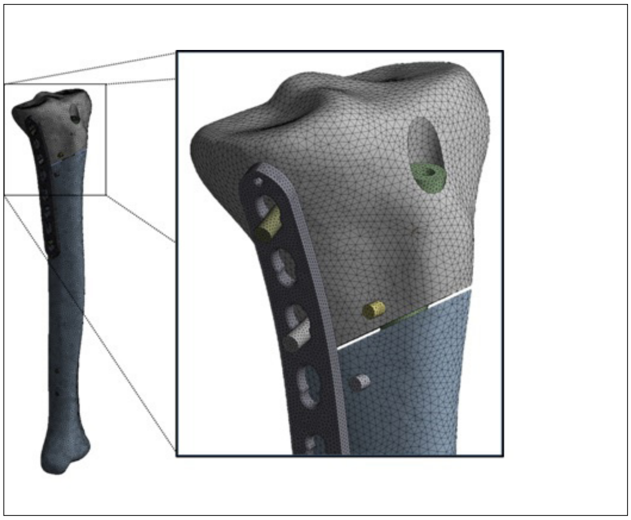

Figure 2. The biomodel meshed using tetrahedral elements.

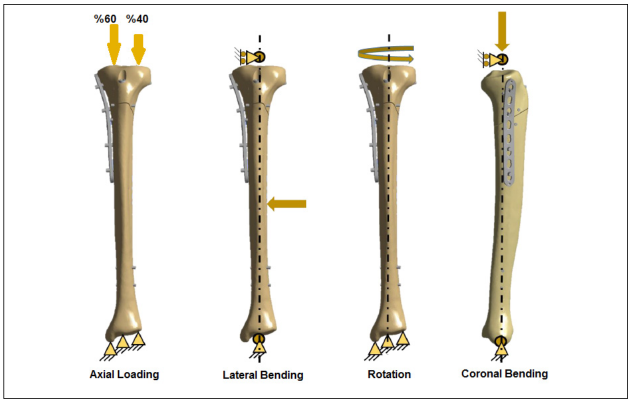

Figure 3. Loading and boundary conditions.

Loading and Boundary Conditions

To compare the different fixation methods in terms of biomechanics, FEA was performed under four different loading conditions. For axial loading, the tibia model was fully fixed distally, with 60% of a 1000 N force applied to the medial plateau and 40% to the lateral plateau. To stimulate lateral bending, a force of 100 N was applied from the lateral region of the tibia under boundary conditions. For rotational loading, the tibia was fixed distally, and a 20 Nm moment was applied proximally. In the coronal bending simulation, a force of 100 N was applied to the tibial shaft (Fig. 3).

A total of 12 analyses were performed for the three different fixation models, with four different boundary conditions. The analysis determined the maximal deformation in the system, the von Mises stresses in the implants, the displacement amount, and the maximum and minimum principal strain in the bone. Biomechanical evaluation was performed on three different fracture fixation methods for unstable fractures of the proximal metaphysis of the tibia using this data.

Table 1. The number of nodes and elements in each model

Variable	Number of Nodes	Number of Elements
Model A	787178	538543
Model B	873661	593465
Model C	921224	624952

Table 2. Material properties

Variable	Elastic Modulus	Poisson's Ratio
Cortical Bone	16700	0.3
Cancellous Bone	155	0.225
Titanium Alloy	114000	0.27

RESULTS

As a result of fracture displacement, tibial principal strain, and the stress values on the nail and plate obtained under four different loading and boundary conditions, it was determined that Model C was biomechanically superior.

Axial Loading

Model A exhibited the highest maximum deformation and displacement among the models under axial loading. The highest von Mises stress (VMS) value in the nail was also observed in Model A, and its location is shown in Figure 4. In Model B, the highest VMS value in the nail occurred in the same region as in Model A, but the measured amount was lower. The highest VMS value on the plate in Model B was higher than in Model C. The main difference between Model C and the other models was the location of the highest VMS on the nail. In Models A and B, it was on the proximal second screw, while in Model C, it was on the distal screw (Fig. 4). The principal strain values in the bone tissue were highest in Model C. The results of the FEA for axial loading are shown in Table 3.

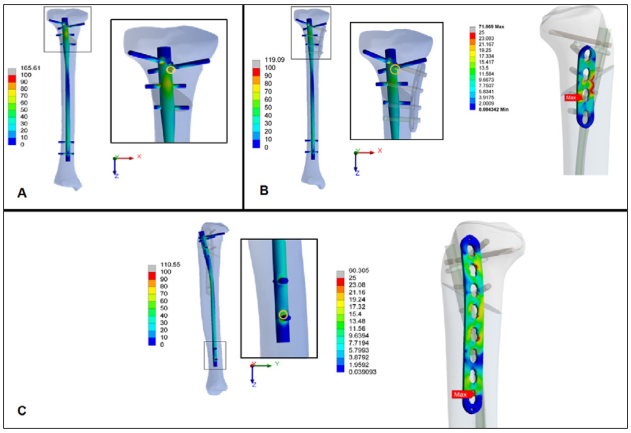

Figure 4. Stress distributions on the models as a result of axial loading.the groups in terms of pulp space and dentin thickness.

Lateral Bending

Under lateral bending, the highest maximum deformation and displacement were observed in Model A. The highest VMS value in the nail and plate was seen in Model C. In Model A, the maximum stress on the nail occurred at the nail body, while in Models B and C, it was observed at the distal part of the nail (Fig. 5). The highest VMS on the plate in Model C was greater than that in Model B. The results indicate that Model C had higher maximum principal strain values, while Model A had higher minimum principal strain values. The results of the FEA for lateral bending are shown in Table 4.

Rotational Loading

Model A exhibited the highest maximum deformation and displacement among the models under rotational loading. The highest VMS value in the nail was seen in Model A and was located in the proximal part of the nail, similar to Model C. In Model B, unlike the others, the highest VMS was observed in the distal locking screw of the nail. The VMS on the plate in Model C was higher than in Model B. Model B had higher maximum and minimum principal strain values (Fig. 6). The results of the FEA for rotational loading are shown in Table 5.

Coronal Bending

Under coronal bending, the highest maximum deformation and displacement were observed in Model A. The highest VMS in the nail was seen in Model A, located in the body of the nail. In Models B and C, the VMS was more prominent in the proximal region of the nail. The VMS on the plate in Model C was higher than in Model B. The results indicate that Model A had higher maximum principal strain values, while Model C had higher minimum principal strain values (Fig. 7). The results of the FEA for coronal bending are shown in Table 6.

Table 3. Finite element analysis results for axial loading

	Model A	Model B	Model C
Maximum deformation (mm)	0.936	0.879	0.878
Maximum stress on the nail (MPa)	165.61	119.09	110.55
Maximum stress on the plate (MPa)	-	71.869	60.305
Displacement (mm)	0.567	0.322	0.285
Maximum principal strain	7129 µ-strain	7361 µ-strain	7664 µ-strain
Minimum principal strain	5860 µ-strain	6730 µ-strain	7063 µ-strain

Table 4. Finite element analysis results for lateral bending

	Model A	Model B	Model C
Maximum deformation (mm)	7.42	7.14	6.90
Maximum stress on the nail (MPa)	70.529	70.637	74.301
Maximum stress on the plate (MPa)	-	20.846	50.669
Displacement (mm)	0.235	0.107	0.079
Maximum principal strain	8844 µ-strain	9013 µ-strain	9213 µ-strain
Minimum principal strain	7930 µ-strain	7734 µ-strain	7768 µ-strain

Table 5. Finite element analysis results for rotational loading

	Model A	Model B	Model C
Maximum deformation (degree)	14.695	14.336	14.191
Maximum stress on the nail (MPa)	332.77	266.93	226.83
Maximum stress on the plate (MPa)	-	99.936	169.96
Displacement (mm)	1.447	1.010	0.656
Maximum principal strain	13692 µ-strain	13918 µ-strain	13865 µ-strain
Minimum principal strain	13132 µ-strain	13630 µ-strain	13224 µ-strain

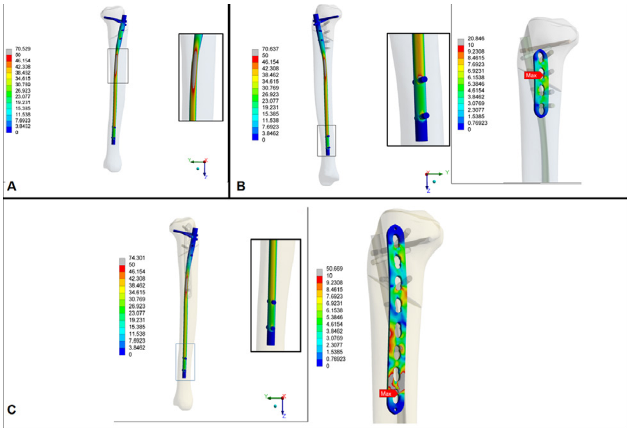

Figure 5. Stress distributions on the models as a result of lateral bending.

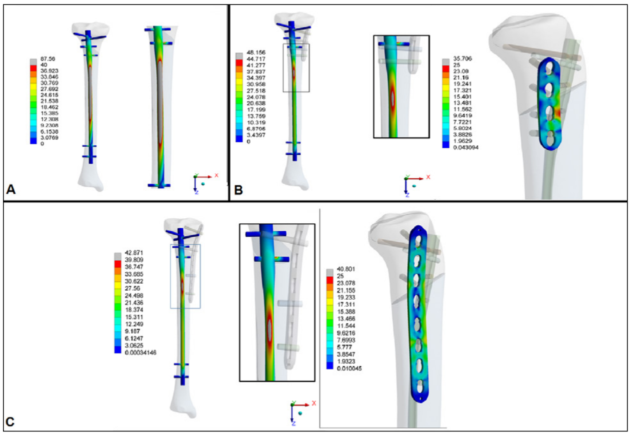

Figure 7. Stress distributions on the models as a result of coronal bending.

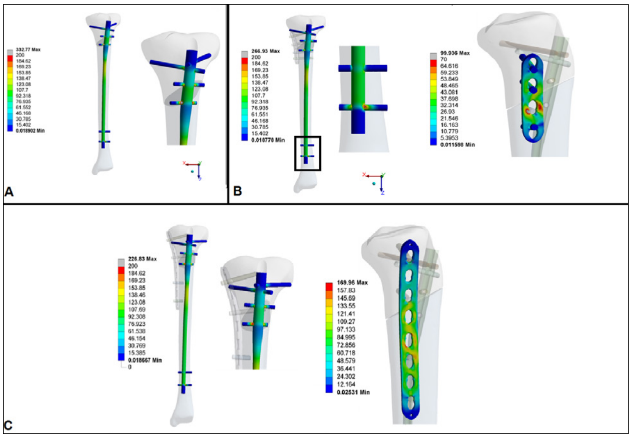

Figure 6. Stress distributions on the models as a result of rotational loading.

DISCUSSION

The biomechanical differences between IMN alone and nail-plate combinations (NPC) under axial loading, lateral bending, rotational loading, and coronal bending were analyzed using FEA to simulate deforming forces. Based on fracture displacement, tibial principal strain, and nail and plate stress values obtained under four different loading and boundary conditions, it was determined that the combination treatment with an 8-hole DCP is biomechanically superior in unstable proximal tibial fractures treated with nails. These findings support our initial hypothesis.

Fancheng Chen et al. created a transverse osteotomy in the tibia 7 cm from the proximal articular surface with a transverse gap of 2 cm and compared IMN fixation to fixation with medial-lateral double plates of different lengths using FEA. In their analysis, only axial loading was applied. The results indicated that the intramedullary fixation method exhibited the highest VMS value compared to other fixation methods. The researchers observed that the highest stress values in all models were concentrated proximally in the screws near the fracture.[11] The results of our study indicated that the maximum stress values observed under axial loading, coronal bending, and rotational loading were significantly higher in Model A. Similar to the Chen et al. study, axial loading caused stress to concentrate in the screws surrounding the fracture in Models A and B. It is noteworthy that in our study, the highest stress on the nail was concentrated on the distal locking screw in Model C under axial loading. We believe that the 8-hole plate acts as a bridge and transfers the stress distally.

Chen et al. found that the models fixed with double plates shared the load with the bone more effectively than those fixed with IMN, and the maximum principal strain was higher in the models fixed with double plates. The amount of displacement in the model fixed with IMN was also observed to be higher than in the other models. They reported that double-plate fixation of proximal tibial fractures would be an appropriate method for young patients with good bone quality and a need for early weight-bearing.[13] In the present study, the amount of displacement at the fracture line was highest in the nail-only model. We observed that the maximum principal strain in the tibia was higher with the combination of nail and plate than with the nail alone. We believe that when the nail is combined with a plate, it transfers some of the load to the bone, and thus provides a significant advantage by delivering a certain amount of compression force required during the fracture healing period and preventing the formation of a stress shield throughout this process.

Wei Feng et al. created a fracture model similar to one used in our study, utilizing 32 cadaveric tibias, and performed biomechanical studies in two different scenarios: under boundary conditions and at the highest values that would disrupt bone morphology in their models. They concluded that IMN has good biomechanical properties but should be used in combination with a plate for proximal tibial fractures.[12] In our study, we applied loading to the models under boundary conditions to mimic physiological loading and did not apply forces that would alter the morphology of the models. It is noteworthy that in our models with NPC, the amount of displacement under all loading conditions, especially during coronal bending, was significantly reduced.

In a clinical study conducted by Sean E. Nork et al. in 2006, 37 proximal metaphyseal fractures of the tibia in 35 patients were treated with IMN. In 13 of these cases, the NPC technique was utilized. They reported no difference in infection rates, union, and time to union between patients treated with the NPC and those treated with nails alone. In conclusion, the authors posited that maintaining reduction in proximal metaphyseal fractures of the tibia is challenging and that the combination of a plate with IMN is an effective approach that is not associated with complications.[13] Similarly, Cinats et al. published a study in 2020 involving 50 patients and found no significant difference in nonunion rates between fractures treated with the NPC and those treated with nails alone. For open fractures, similar rates of nonunion and infection were reported.[14] The majority of orthopedic surgeons believe that open reduction may delay union or cause nonunion. However, the results of these clinical studies indicate that open reduction and NPC treatment do not have a negative effect on union. Furthermore, these studies demonstrate that utilizing NPC treatment in open fractures with significant soft tissue injuries is associated with a low risk of infection. Nevertheless, we believe that multicenter prospective randomized trials with a large number of patients should be conducted to determine the effect of NPC treatment on infection and nonunion.

Implant failure due to metal fatigue occurs at stress points, such as screw holes.[15] Laflamme et al. reported that two additional oblique screws placed proximal to the fracture contributed up to 50% to fracture stability.[16] In the present study, we used a total of four proximal locking screws-two transverse and two oblique screws, perpendicular to each other-with the intramedullary nails applied to the models. The results of the FEA indicated that the highest stresses in the nail were concentrated on the proximal screws under axial and rotational loading. In proximal metaphyseal fractures of the tibia, we believe that the use of oblique locking screws in addition to proximal transverse locking screws is biomechanically more stable, if the nail design allows.

CONCLUSION

The choice of fixation method for unstable proximal tibial fractures represents a significant challenge for surgeons. The results of this study indicate that the combination treatment with an 8-hole DCP is biomechanically superior in unstable proximal tibial fractures treated with nails. Although the nail-plate combination requires an additional surgical incision and extra implants, it offers advantages in terms of stability and sustainability of reduction for unstable fractures. Finite element analysis is a promising technique that may be employed in the future as a routine component of surgical planning.

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Conflict of Interest: None declared.

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DENEYSEL ÇALIŞMA - *ÖZ*

İnstabil tibia proksimal metafiz kırıklarının tedavisinde sadece kanal içi çivi ve çivi-plak kombinasyonlarının sonlu eleman analizi

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AMAÇ: Proksimal tibianın anatomisi tedavi güçlükleri sunar ve bu bölgenin kırıklarında şu anda yaygın olarak yerleşmiş bir cerrahi tespit yöntemi yoktur. Çalışmamızın amacı sadece kanal içi çivi ve çivi-plak kombinasyonları ile tespitin karşılaştırmasını sonlu eleman analizi ile yapmaktır. Bu çalışmanın amacı tibia proksimal metafizer bölgenin stabil olmayan kırıklarında 4 delikli LC-DCP (Limited Contact Dynamic Compression Plate) plak kombinasyonlu kanal içi çivileme ile 8 delikli LC-DCP plak kombinasyonlu kanal içi çivilemenin (KİÇ) etkinliğini, faydasını ve farkını sonlu elemanlar analiziyle (SEA) değerlendirmektir.

GEREÇ VE YÖNTEM: Tibia modelleri üzerinde metafizer bölgede, anteriorda diz ekleminin 5 cm distaline ve posteriorda diz ekleminin 8 cm distaline gelecek şekilde sagital düzlemde 30 derece açı oluşturan oblik kırık oluşturuldu. Üç adet tibia kullanılarak modeller oluşturuldu. Modellerden birine sadece kanal içi çivi uygulandı, diğerlerine ise çiviye ek olarak 4 delikli plak ve 8 delikli plak uygulandı. Bu modellerin 3 boyutlu bilgisayarlı tomografi görüntüleri kullanılarak sonlu eleman analizi yapıldı. Modellemeler üzerine aksiyel, lateral, koronal ve rotasyonel zorlamaların sonucunda oluşan deformasyon, deplasman, Von mises stres ve maksimum asal gerinim değerleri analiz edildi.

BULGULAR: Tüm zorlamalar sonucunda yalnızca çivi ile tespit modelinde maksimum stres miktarının, maksimum deformasyonun ve deplasman miktarının fazla olduğunu gözlemledik. Aksiyel yüklenmede; çivi ve 8 delikli plak kombinasyonunda diğer modellerden farklı olarak çivideki en yüksek stres miktarının distal kilitleme vidası üzerinde yoğunlaştığını gördük. Tibiada oluşan maksimum asal gerinim, çivi ve plak kombinasyonuyla tespiti gösteren modellerde, yalnızca çivi ile tespit modeline göre daha fazla olduğunu gözlemledik.

SONUÇ: Bu çalışmanın sonuçları çivi ile tedavi edilen instabil tibia proksimal kırıklarında 8 delikli plak ile kombinasyonlu tedavinin biyomekanik olarak daha üstün olduğunu göstermektedir. Plak kombinasyonlu çivi tedavisi ek cerrahi insizyon ve ek implant gerektirse de instabil kırıklar için redüksiyonun kalitesi, stabilitesi ve sürdürülebilirliği açısından avantajlıdır.

Anahtar sözcükler: Biyomekanik; sonlu eleman analizi; tibia kırıkları.

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