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Influence of the Intramedullary Nail Length on a Fracture Site: Biomechanical Evaluation with the Finite Element Method

İntramedüller Çivi Uzunluğunun Kırık Sahasına Etkisi: Sonlu Eleman Yöntemi ile Biyomekanik Değerlendirme

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Abstract

Introduction: Intramedullar locking nails have been widely preferred in femoral shaft fractures, however, design of the nails causes some problems. If the length of the nail and the distance of the distal locking screws to the fracture site are not considered, negative side effects may be observed. In order to understand the side effect of the distance between fracture gap and the distal locking pin, effect of the nail length were aimed to investigate in this study.

Material and Method: Two conventional intramedullary nails with different lengths were compared. One nail was 301 mm and the other nail was 251 mm in length. The nails were inserted into the 1/3 proximal fractured femur with the support of computer-aided design software. Comparative Static analyses were performed on the three-dimensional models.

Results: Different equivalent (von-Mises) stress results were observed on the fracture sites of the two models which were 2.02 GPa and 31.93 MPa respectively. Consequently, the stress on the fracture surface decreases as the distance between the distal locking site and the fracture site, decreases.

Conclusion: Clinically, the shorter nail must be preferred to decrease the stress on the fracture site. Meanwhile, the other factors like diameter, angle of the fixation pin, and material properties should be considered while choosing nails.

Keywords: Intramedullar nail, distal locking, stress analysis, biomechanics, finite element

Öz

Amaç: Femoral şaft kırıklarında yaygın olarak intramedüller kilitli çiviler tercih edilmektedir, ancak çivi tasarımları ve boyutları kırık sahasını ve kemiğin iyileşmesini farklı etkilemektedir. Çivinin uzunluğu ve distaldeki sabitleme vidalarının kırık sahasına uzaklığı dikkat edilmez ise olumsuz yan etkiler gözlemlenebilir. Bu çalışmada, kırık sahası ile distal sabitleme vidaları arasındaki mesafenin iki kırık fragmanı arasındaki etkileri gözlemlenmiştir.

Gereç ve Yöntem: Farklı uzunluktaki iki intramedüller çivi karşılaştırılmıştır. Çivilerden biri 301 mm, diğer çivi 251 mm boya sahiptir. Çiviler 1/3 proksimal kırık modeli oluşturulmuş femura bilgisayar destekli tasarım yazılımı desteği ile yerleştirilmiştir. Oluşturulan 3D modeller üzerinde karşılaştırmalı statik analizler yapılmıştır.

Bulgular: İki modelin analiz sonrası kırık sahasında gösterdikleri von-Mises gerilmeleri sırasıyla 2,02 GPa ve 31,93 MPa olarak gözlemlenmiştir. Sonuç olarak distal kilitleme tarafı ile kırık sahası arasındaki mesafe azaldıkça kırık yüzeyindeki gerilimin de azaldığı görülmüştür.

Sonuç: Klinik olarak kırık tarafındaki stresi azaltmak için daha kısa intramedüler çivilerin tercih edilmesi gerektiği sonlu elemanlar analizi ile saptanmıştır. Ayrıca, çivi tercihi yapılırken çap, sabitleme vida açısı ve malzeme özellikleri gibi diğer faktörlere de dikkat edilmelidir.

Anahtar Kelimeler: İntramedüller çivi, distal kilitleme, mukavemet analizi, biyomekanik, sonlu elemanlar analizi

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INTRODUCTION

The intramedullary nail or rod is commonly used for long-bone fracture fixation and has become the standard treatment of most long-bone diaphyseal and selected metaphyseal fractures. Intramedullar locking nailing has been widely accepted for femoral shaft fractures, but mechanical failure still remains a problem.[1-4] To fully understand the use of intramedullary nail, a basic knowledge about biology and biomechanical features of nail is necessary. These implants are located into the bone to remote the fracture healing process by sharing compressive, bending, and torsional loads with the surrounding osseous structures. Intramedullary nails function as internal splints that allow for secondary fracture healing. Many studies have demonstrated that stress is high at the proximal distal screw or around the proximal distal screw hole of the nail, leading to frequent mechanical failure of the implants.[5,6] The stress of the locking screws is, in fact, remarkably influenced by the fit of the nail or the extent of nail-cortical contact in the medullary canal.[7,8] However, there have been no studies about the right distance of the distal locking screws from the fracture site. The model was used to investigate the stress of the fracture site by comparing two nails with different length. According to the length, the distal locking distances from the fracture site were different, however, the distances of the proximal lockings were same. Any important study on that subject hadn't been noticed. The relation between the fracture site and the distal locking screws' distance to the fracture site was considered.

In this paper, a finite element model including a intramedullary nail within a fractured femur was used to investigate the stresses between the fomaral fragments and the effects of nails at different lengths.

MATERIAL AND METHOD

To fully understand the reasons behind the greater biomechanical stability afforded by length of the nail, a finite element study was conducted. Recently, it becomes very useful and easy to estimate the stresses with computers by courtesy of developing computer tecnhnology. Especially three-dimensional (3D) finite element analyses of the prosthesis are now prevalent. In this study, the comparative finite element analysis allowed nail length to be isolated as the sole variable of the investigation. Two finite element models were constituted in which the bone material properties, nail materials, nail location, loading and boundary conditions were identical and constant while the nail length was varied to be either 301 mm or 251 mm (**Figure 1**).

The Bone Model

The computer aided design (CAD) of a 3D femur was downloaded as Initial Graphics Exchange Specification (IGES) surface definitions of the cortex from the mesh repository. This external geometry was created by the Allesandro Chiarini; it is available on the Internet through the Biomechanical European Laboratory (BEL) Repository managed by the Istituti Ortopedici Rizzoli, Bologna, Italy.[9] This physical IGES model has been used in a number of biomechanical studies involving intramedullary nails.[10-12] In this study, first of all the femur model was imported into solid design software (Autodesk Inventor Professional 11) where the geometry of nails, and the comminuted fracture, all consistent with the femur geometry, were added. The fracture was constituted at 160 mm below the tip of the trochanter major with an 1mm fracture gap. That fracture was just created at any point on the femoral shaft. The fracture type was not so important, because all circumstances were same accept intramedullary nail length and the distal locking screw position on the femur as well. The first fixation pinhole on the femur from the proximal part was 80 mm above the fracture site, and 12 mm distance were constituted between two proximal holes according to the intramedullar nail geometry (**Figure 1**).

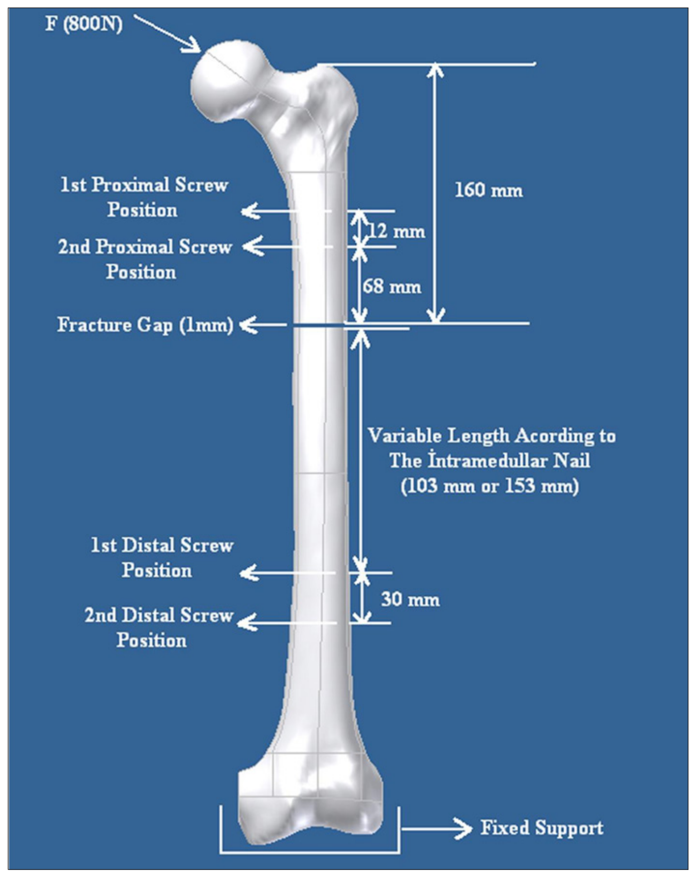

Figure 1. The illustrated constants of the designs on femur.

The Nail Model

The design of the intramedullary nail was same as the conventional nails. Nail geometry was not so important, because comparison of the nail length's effect on fracture site was examined in the study.

Nail lenght directly related with the distal locking screw position on the distal fractured femoral fragment. The materials of intramedullary nail and its fixation pins were chosen as stainless steel, because of its superior fracture stability due to its higher elastic modulus. The radius of the nail is 12 mm at the proximal part and 10 mm at the distal part. It is designed in two lengths of 301 mm and 251 mm respectively (**Figure 2**). The curvature radius of the nail is 1500 mm and that is the same as the Schneider's design.[13] The cross-section of the nail is circular. The distal screws and the proximal screws have a diameter of 5 mm.

Finite Element Model

A 3D finite element model of the system including the intramedullary nail and the fractured femur, as shown in **Figure 2**. The model was constructed by using the ANSYS WORKBENCH finite element software. Ten-noded tetrahedron elements and point-to-surface contact elements were used throughout. The version of the software (ANSYS WORKBENCH 9.0) permitted only linear elements to be used in conjunction with contact elements.

The cortical bone was modelled with a value of 18.6 GPa for its modulus of elasticity. The material properties were modelled as homogeneous linear elastic continua exhibiting isotropic properties. A value of 0.33 was assigned to all material as a Poisson's ratio.

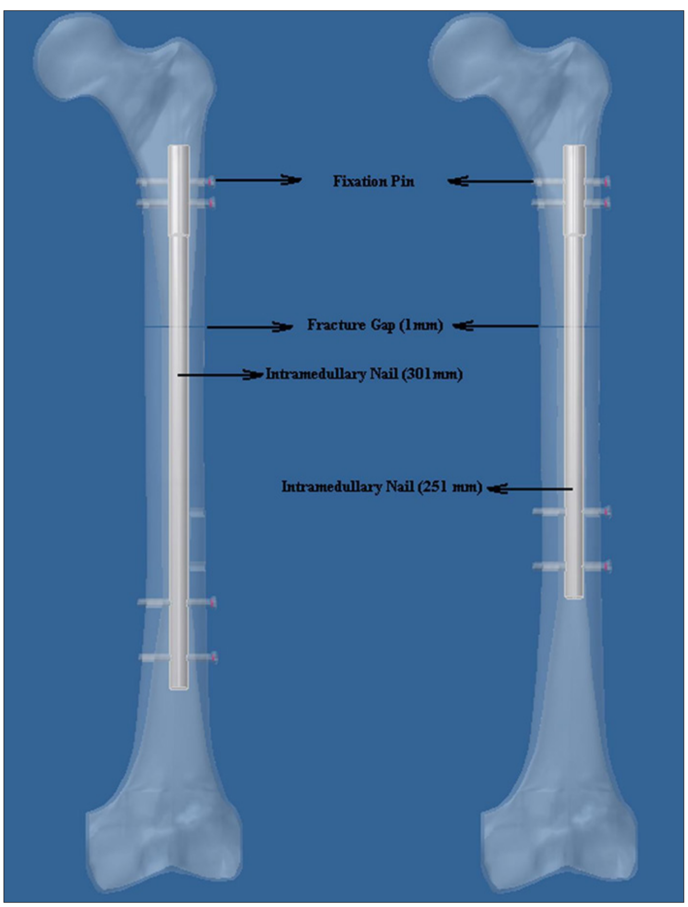

Figure 2. Transparent view of the femur after implantation of the intramedular nails.

The intramedullar nail was modelled as stainless steel, with a value of 193 GPa for its modulus of elasticity. The material properties were modelled as homogeneous linear elastic continua exhibiting isotropic properties. A value of 0.31 was assigned to all material as a Poisson's ratio.

For the system with a nail that is 251 mm in length, 29840 Nodes and 15069 Elements were used in the meshing process. For the other system with a nail that is 301 mm in length, 29569 Nodes and 15013 Elements were used in the meshing process (**Figure 3**).

Figure 3. Meshing of the designs

RESULTS

Two systems, including intramedullary nails which were in different lengths, were investigated. For each system same load conditions was applied. The lower fragments for each systems are seen in **Figure 4**. In this figure, the lower fragments can be seen from the fracture site (upside), so the stress distribution can be observed easily. As it is seen, in the shorter intramedullary nail (b), the stress effects on the fracture site are low. By this way, the fixation is more stable. The results are 2.0204e+009 Pa and 3.1925e+007 Pa respectively. If you compare the results, the stresses are more influential in the longer nail.

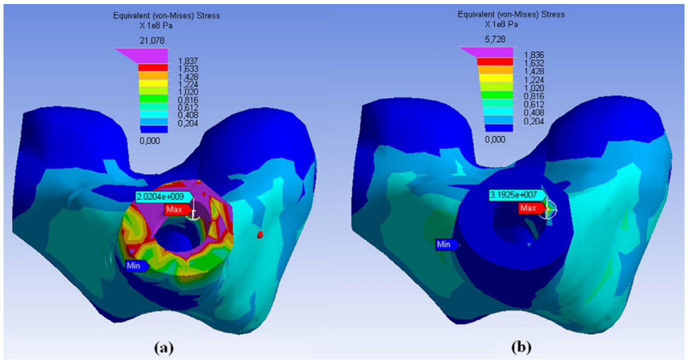

Figure 4. Equivalent Stress distributions at the fracture site on a lower part of the femur. **(a)** The result with longer intramedular nail, **(b)** the result with shorter intramedular nail.

DISCUSSION

The choice of treatment for early mobilization of femoral fractures in surgery is using plates and screws or the intramedullary nails.

Fracture treatment by means of intramedullary nails[14,15] is an accepted and widely used method of treating transverse and short oblique, axially stable fractures of the femoral diaphysis. Biomechanically, the intramedullary propping nailing system is safe and able to provide good abutment of the nail to the bone.[10] If the intramedullary nail is well fixed, then the healing will be faster. Although, the stable fixation of the intramedullary nail is important, type of the fractures significantly affects the performance of the fixing nail. There are many commercial types of intramedullary nails but most of them have similar biomechanical properities, and also there are too many studies about the material proporties and its' effects on the stabilisation of the nail. For instance, experimental testings evaluating different materials for femur fixation, have reported that the titanium alloy is biomechanically more stable than the stainless steel. This experimental data required computational verification, as the clinical interpretation of the experimental data was not intuitive.[16] However, about the stres distrubition under loading hasn't studied enough.

Significant forces are present in the long bones, but their magnitudes have so far only been estimated from mathematical models.[13] There are some studies on the stress distrubiton of intramedullary nail but the nail's distal length and screw position hasn't been studied untill this study.

In locked nailing, the distance between the distal locking site and the fracture site is very important for stable fixation. There are lots of biomechanical studies about the stress analysis on the screws. They have shown that the stress on the screws is substantially affected by the fiting of the nail in the medullary canal. However, well fiting of the nail doesn't solve the stress problems every time. At that point, the distance between the distal locking site and the fracture site should be studied.

Acording to the mathematical model in this study, the stress of the fracture site is substantially affected by the distance of the distal locking screw. This finding is important for nail designing. Lin et al.[7] found that an increase of the nail fitness or the nail cortical contact increased the fixation stability in a biomechanical test of humeral nailing. The results of this study agree with this observation, because the low stress on the fracture surface shows more stable fixation.

CONCLUSION

Consequently, the fracture site stress distrubution changes with the distance between fracture site and locking screw position. We hope to continue this study to observe the effects of the screw angles, positons and the nail diameters on fracture surfaces.

ETHICAL DECLARATIONS

Ethics Committee Approval: There is no need for an ethics committee decision for the study.

Referee Evaluation Process: Externally peer-reviewed.

Conflict of Interest Statement: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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