ORIGINAL ARTICLE

Finite element analysis of the effect of intramedullary nail compression amount on fracture union in distal tibial diaphyseal fractures

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ABSTRACT

BACKGROUND: The objective of this study was to investigate the relationship between the stress values on the fracture surface and union periods seen in cases of different compression amounts used to manage distal tibial diaphyseal fractures treated with intramedullary nailing (IMN).

METHODS: Ninety-five patients (mean age: 33.99±10.65 years; male: n=78, female: n=17) with tibial shaft fracture were included in the study. The patients were divided into 3 groups: No compression was used in Group 1 (33 patients), and dynamic compressive fixation was performed with IMN in Group 2 (1 mm, 32 patients) and Group 3 (1.5 mm, 30 patients). A finite element study was performed for Group 2 and Group 3.

RESULTS: The average time to achieve radiological union was 16.08±2.02, 13.54±1.52, and 12.56±1.73 weeks in Groups 1, 2, and 3, respectively. Comparatively, the union period in the non-compression group was significantly longer ($p<0.001$). The functional results were evaluated as excellent in 28 (85%) patients and good-medium in 5 (15%) in Group 1, excellent in 27 (92%) and good-medium in 5 (8%) in Group 2, and excellent in 26 (92%) and good-medium in 4 (8%) in Group 3.

CONCLUSION: IMN is a highly effective treatment method for tibial shaft fracture.

Keywords: Compression; fracture union; intramedullary nail; nonunion; tibia distal diaphyseal fracture.

INTRODUCTION

Distal tibial diaphysis fractures constitute 10% of all tibial fractures.[1] The objectives of surgical treatment are to protect the sagittal and coronal alignments, arrange bone length and rotation, and provide early range of motion of the knee and ankle.[2] Serious soft tissue injuries, malunion, nonunion, and infection frequently accompany these fractures.[3]

Intramedullary nailing (IMN) is a widely used treatment method for tibial fractures, and it provides a functional result that is superior to conservative treatments.[4,5] It provides adequate mechanical stability with better fracture alignment.[6] Interlocked nails may be inserted with or without reaming or compression, and there are static, dynamic, and dynamic compression alternatives. The decision to use reaming in IMD remains controversial.[7]

Using active compression on the fracture line accelerates the fracture union process.[8,9] The present study is an assessment of the effect of different compression methods on the fracture union period in INM patients. In addition, the stress values on the fracture surface according to the compression amount applied were examined in a finite element study.

MATERIALS AND METHODS

The data of 95 patients who had a tibial shaft fracture (mean age: 33.99±10.65 years; male: n=78, female: n=17) between

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2006 and 2016 were retrospectively examined. In this study, only patients with closed fractures that were classified as 43-A1, 43-A2, and 43-A3 in accordance with the AO classification were included; those with other diseases were excluded. The study patients were divided into 3 groups: Group 1 comprised 33 non-compression patients, Group 2 was made up of 32 patients for whom 1 mm of compression was applied, and 30 patients who had 1.5 mm of compression applied were included in Group 3. In Group 1, static interlocked nailing was used without compression after reaming. In Group 2 and 3, dynamic compression interlocking was performed after reaming and insertion of the intramedullary compression nail.

Notably, none of the patients required postoperative splinting or bracing. All of the patients wore an anti-embolism stocking for 4 weeks. Low molecular weight heparin was used for a period of 4 weeks, and 1 g intravenous cefazolin sodium was administered 3 times within a period of 24 hours after the procedure. X-ray images of the patients captured following the surgery and during follow-up were evaluated according to the criteria of the radiographic union score for tibial fractures, and functional results were evaluated in accordance with the Johner–Wrush criteria. A finite element study was performed to examine the 1-mm and 1.5-mm compression applied in Groups 2 and 3, respectively. One-way analysis of variance (ANOVA), Fisher's exact test, Pearson's chi-squared test, Mann-Whitney U test, and Student's t-test were used to statistically evaluate the data.

This study was approved by Antalya Training and Research Hospital ethical committee of clinical research approval was obtained for the study. Ethical protocol number of the research is 2018-132 and informed consent was obtained from all participants included in the study.

Surgical Technique

All patients were in the supine position when the fracture line was accessed. The patellar tendon was longitudinally accessed in all cases via a transtendinous approach. Reaming was performed using a superior entry from the proximal tibia following the reduction. A nail of appropriate length and diameter was inserted in the apex position such that the tibial plateau was lower than the level of the anterior side. Distal interlocking was first performed with 2 interlocking screws, followed by the proximal dynamic hole with a single screw in Groups 2 and 3. The distal interlocking was performed using the technique described by Aldemir et al.,[8] but without fluoroscopy. The application of 1-mm and 1.5-mm compression was performed by rotating the screw 1 or 1.5 turns, respectively, enabling the interlocking screw to pass through the dynamic hole and engage with the nail. All of the compression screws were applied in the proximal end. The compression screws were statically locked in Group 1. Finally, the apex screw was inserted and the procedure was completed.

Statistical Analysis

Descriptive statistics were presented as mean±SD, median (min-max), and n (%) values, as appropriate. Fisher's exact test and Pearson's chi-squared analysis were performed for categorical variables. Student's t-test was used for comparison of 2 groups, and one-way ANOVA was used for the comparison of the 3 groups with normal distribution. The Mann-Whitney U-test was used to assess quantitative variables with non-normal distribution. The statistical analysis was performed using IBM SPSS Statistics for Windows, Version 21.0 (IBM Corp., Armonk, NY, USA). A p value <0.05 was considered statistically significant.

Finite Element Analysis

Nonlinear analysis was performed using 3-dimensional (3D) finite element stress analysis. A computer equipped with Intel Xeon R CPU (Intel Corp., Santa Clara, CA, USA), 3.30 GHz microprocessor, 500 GB hard disk, 14 GB RAM, and Windows 7 Ultimate Version Service Pack 1 operating system (Microsoft Corp., Redmond, WA, USA), a 3D scanning device with Activity 880 (Smart Optics, Sensortechnik GmbH, Bochum, Germany) optical scanner (Fig. 1), Rhinoceros 4.0 3D modeling software (Robert McNeel & Associates, Seattle, WA. USA) and VRMesh Studio (VirtualGrid Inc., Bellevue City, WA, USA), and ALGOR FEMPRO (ALGOR, Inc., Pittsburgh, PA, USA) analysis programs were used to create a 3D network structure and homogeneous conditions based on 3D solid model and finite elements stress analysis.

To perform the analysis, the models were transferred to the ALGOR FEMPRO software in .stl format after they were cre-

Figure 1. Activity 880 (Smart Optics, Sensortechnik GmbH, Bochum, Germany) optical scanner.

Table 1. Comparison of time to bony union in the study groups

	Time to bony union	p
	Mean±SD	
Non-compression	16.08±2.02	0.001*
1-mm compression	13.54±1.52	
1.5-mm compression	12.56±1.73	

*P<0.001.

ated geometrically using the VRMesh software. The .stl format is universally applicable to 3D modeling programs; there is no information loss during transfer between programs. However, it is necessary to identify the bone structure components. The material values (elasticity module and Poisson's ratio) identifying the physical properties were fed into each structure of the models.

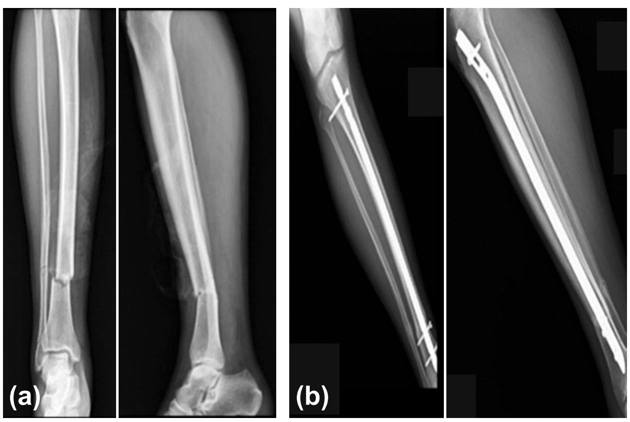

Figure 2. (a) Preoperative radiographs of a 38-year-old male patient with right distal diaphyseal tibia fracture extending to the metaphysis resulting from a fall. **(b)** Radiographs of the patient in the first year of follow-up after intramedullary nailing with 1.0-mm compression.

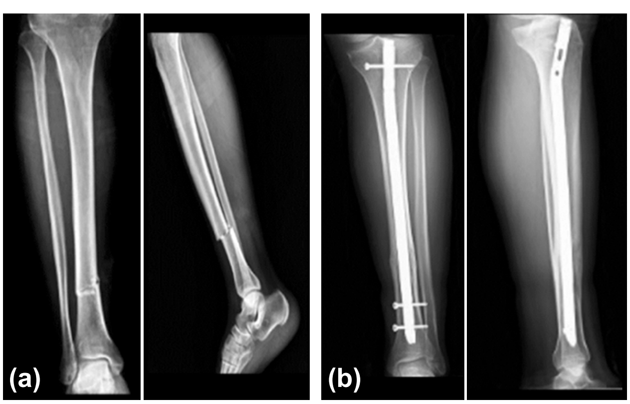

Figure 3. (a) Preoperative radiographs of a 32-year-old female patient with right distal diaphyseal tibia fracture extending to the metaphysis resulting from a fall. **(b)** Radiographs of the patient in the first year of follow-up after intramedullary nailing with 1.5-mm compression.

Two materials were used in the analyses. The first was the cortical bone material, which has the mechanical properties of an elasticity modulus of 20 GPa, a Poisson's ratio of 0.15, and a density of 1650 kg/m^3. The mechanical properties of the titanium screws used were an elasticity modulus of 96 GPa, a Poisson's ratio of 0.36, and a density of 4620 kg/m^3.

Positive values in the analysis results indicated tensile stress and negative values indicated compression stress.

RESULTS

Union was achieved in all of the study patients. The union periods are shown in Table 1. The mean time to radiological union was 16.08±2.02 weeks in Group 1, 13.54±1.52 weeks in Group 2, and 12.56±1.73 weeks in Group 3. The union period for the non-compression group was statistically significantly longer than that of the other 2 groups ($p<0.001$). No statistically significant difference was found between the 1-mm and 1.5-mm compression groups (Fig. 2 and 3).

The functional results were evaluated as excellent in 28 (85%) patients and good-medium in 5 (15%) in Group 1, excellent in 27 (92%) and good-medium in 5 (8%) in Group 2, and excellent in 26 (92%) and good-medium in 4 (8%) in Group 3. Anterior knee pain was observed in only 5 patients.

No instance of infection, compartment syndrome, or thromboembolism was observed in any of the patients. The finite element study revealed that the average stress value was

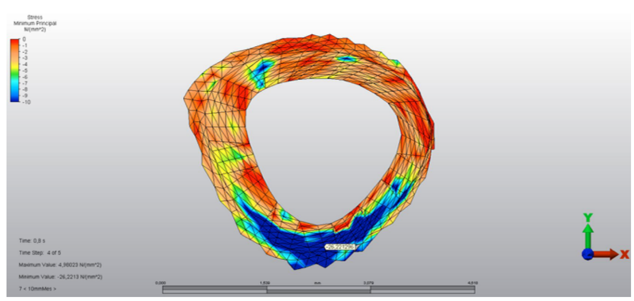

Figure 4. Stress on the fracture surface when the screw is inserted at 1.0 mm.

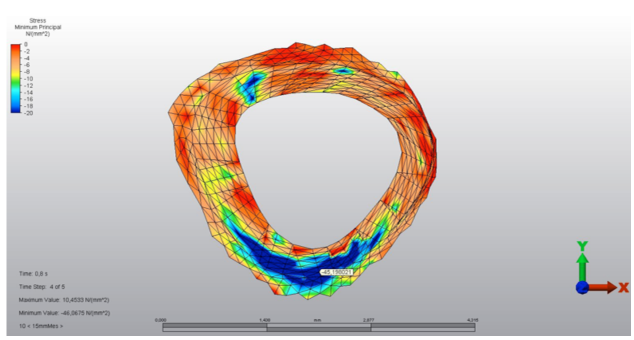

Figure 5. Stresses on the fracture surface when the screw is inserted at 1.5 mm.

26.22 MPa in the 1-mm compression group and 45.2 MPa in the 1.5-mm group.

DISCUSSION

Intramedullary interlocking compression nails can reduce the length of the fracture union period in patients with tibial fracture.[9] In our study, the union period was much shorter in Groups 2 and 3 (compression) when compared with that of Group 1 (non-compression). No statistically significant difference was found between Groups 2 and 3 in terms of the length of the union period. Therefore, we believe that greater compression is not required in tibial shaft fracture types AO A2, A3, and B2.

Högel et al.[10] compared the strength value of compression screws and bone fixation screws used in diaphyseal tibial fractures. They reported a mean postoperative compression load of 1852 N (range: 362–4325 N) that was 980 N (range: 188–2550 N) 4 weeks later. Högel et al. did not mention stress value on the fracture surface in their study. We performed a finite element study with the hypothesis that the stress value on the fracture surface would be useful. In our study, the pressure distribution in the tibial fracture region was calculated according to the amount of compression applied (1 or 1.5 mm). The axial strength mentioned in Högel et al.'s work and the overloads that resulted from the bending moment that this strength created in the fracture section had an effect on this distribution.

In an experimental study conducted by Baki et al.[11] using rabbits, they demonstrated the effects of different compression levels on fracture union. They applied 0.5-mm and 1-mm compression to the fracture surface and subsequently conducted finite element studies. They reported stress values of 34.5 MPa in the 0.5-mm compression group and 88 MPa in the 1-mm compression group. In addition, they found that the union was histologically better and was achieved sooner in the 34.5 MPa group. Our finite element study revealed that the average stress value was 26.22 MPa in the 1-mm compression group and 45.2 MPa in the 1.5-mm compression group (Fig. 4 and 5).

The axial load and tensile values were determined when they were subjected to linearly varying deforming powers due to the inclined structure of the tibia (e.g., 26.22 MPa in 1-mm compression and 45.2 MPa in 1.5-mm compression). The tensile value of the fracture in certain anatomical regions represents a nonlinear relationship due to the anatomical curve in the femur (e.g., 34.5 MPa in 0.5-mm compression and 88 MPa in 1-mm compression). An average stress value of 50 MPa was measured with 1-mm compression in humeral shaft fractures.[12] Therefore, the stress values obtained in a finite element study with the same degree of compression applied to the humerus, femur, and tibia varied due to the different anatomical curves and fracture surface fields of the bones. The compression required to create stress values between 34 MPa and 88 MPa were found to be ideal, which was consistent with the results of the experimental study of Baki et al. and with our clinical results. We believe that the MPa parameter showing surface stress tension is more important than mm and Newton parameters indicating compression.

While some authors have suggested the use of the backstroke technique, Mückley et al.[13] reported that compression was a superior means of attaining initial stability. The backstroke technique had not been used in any of the patients whose reduction was completed.

A number of authors have mentioned anterior knee pain occurring at different ratios in their patients after IMN in tibial shaft fractures.[14,15] We found anterior knee pain in only 5 (7%) patients. All of these were cases in which the nail was at a higher level; the pain findings were independent from the application of compression.

Infection was not seen in any of our cases. To the best of our knowledge, this is the first study in humans to examine both the compression and fracture surface stress values in the treatment of tibial shaft fracture.

Limitations of this study include the retrospective design and the fact that we were only able to examine tibial distal end fractures. Further study of proximal fractures is required due to the surface difference.

Conclusion

The use of interlocking compression nails in AO A2, A3, and B2 tibia distal end fractures substantially shortens the fracture union period. There was no statistically significant difference in terms of the union period between a 1-mm compression group and a 1.5-mm group. We believe the stress value that occurred on the fracture surface is an important loading parameter in compression.

Conflict of interest: None declared.

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ORİJİNAL ÇALIŞMA - *ÖZET*

Tibia distal diafiz kırıklarında intramedüller çivi kompresyon miktarının kırık kaynaması üzerine etkisinin sonlu eleman analizli değerlendirilmesi

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AMAÇ: Intramedüller çivi (IMN) uygulanan tibia distal diafiz kırığı olgularında farklı kompresyon miktarlarının kırık yüzeyindeki stres değerleri ve kaynama süreleri arasındaki ilişkiyi araştırmak.

GEREÇ VE YÖNTEM: 2006–2016 yılları arasında tibia cisim kırığı olan 95 hasta çalışmaya alındı. AO sınıflamasına göre 43-A1, 43-A2, 43-A3, Gustillo-Anderson sınıflamasına göre kapalı kırık olan hastalar çalışmaya alındı. Yetmiş sekiz hasta erkek, 17 hasta kadın olup ortalama yaş 33.99 (SS± 10.65) idi. Hastalar üç gruba ayrıldı. Grup 1'de (33 hasta) kompresyon yapılmadı. Grup 2'de (32 hasta) ve 3 (30 hasta) IMN ile dinamik kompressif tespit yapıldı. Kompresyon miktarı Grup 2'de 1 mm, Grup 3'de 1.5 mm olarak uygulandı. Hastaların ameliyat sonrası ve takiplerinde çekilen röntgen grafileri Rust kriterlerine göre, fonksiyonel sonuçlar ise Johner-Wrush kriterlerine göre değerlendirildi. Ayrıca Grup 2 ve 3'de uygulanan 1 mm ve 1.5 mm kompresyon ile ilgili sonlu eleman çalışması yapıldı. İstatistiksel olarak tek yönlü Anova, Fisher kesin testi, Pearson ki-kare, Mann-Whitney U-test ve Student t-testleri kullanıldı.

BULGULAR: Bütün hastalarda kaynama elde edildi. Radyolojik kaynama Grup 1'de ortalama 16.08 (SS±2.02) hafta, Grup 2'de 13.54 (SS±1.52) hafta ve Grup 3'de 12.56 (SS±1.73) haftada sağlandığı görüldü. Kompresyon uygulanmayan grupta kaynama süresi, kompresyon uygulanan diğer gruplara göre anlamlı düzeyde uzundu ($p<0.001$). Fonksiyonel sonuçlar Grup 1'de 28 (%85) hasta mükemmel, beş (%15) hasta iyi-orta, Grup 2'de 27 (%92) hasta mükemmel, beş (%8) hasta iyi-orta, Grup 3'de 26 (%92) hasta mükemmel, dört (%8) hasta iyi-orta olarak değerlendirildi. Toplam beş hastada diz önü ağrısı mevcuttu. Hiçbir hastada enfeksiyon görülmedi.

TARTIŞMA: Kilitli kompressif çiviler tibia cisim kırıklarında oldukça etkin bir tedavi yöntemidir. Çivi üzerinden uygulanan kompresyon kaynama süresini belirgin şekilde kısaltmaktadır.

Anahtar sözcükler: İntramedüller çivi; kırık kaynaması; kompresyon; nonunion; tibia distal uç kırığı.

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