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Farklı Taper Açılarına Sahip Endodontik Eğelerin Biyomekanik Özelliklerinin Sonlu Elemanlar Analiziyle Değerlendirilmesi

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Öz

Bu çalışma, farklı taper açılarına sahip nikel-titanyum (Ni-Ti) döner aletlerin bükülme ve burulma sırasındaki gerilim dağılımını sonlu elemanlar analizi (SEA) kullanılarak değerlendirilmeyi amaçlamaktadır. Çalışma için 0.02, 0.04 ve 0.06 sabit taper açılarına sahip döner alet eğeleri Solidworks yazılımı kullanılarak modellendi. Bu modeller ANSYS yazılımına aktarıldı. Eğelerin esnekliğini ve burulma sertliğini değerlendirmek için SEA yöntemi kullanılarak, ISO 3630-1 spesifikasyonuna göre testler gerçekleştirildi. Test sonuçlarına göre 0.02 taper açısına sahip eğe sistemi bükülmeye maruz kaldığında 0.04 ve 0.06 tapera sahip eğelerden daha yüksek esneklik gösterdi. Burulma direnci açısından 0.06 taper açısına sahip döner eğe, 0.02 ve 0.04 taper açısına sahip eğelerden daha yüksek burulma direnci gösterdi. Aletin geometrisi, döner eğelerin mekanik davranışını (bükülme ve burulma) etkilemektedir. Klinisyen döner eğelerdeki davranışsal farklılıkların farkında olmalı, üretici talimatlarına ek olarak klinik duruma göre uygun eğeyi kullanmalıdır.

Anahtar kelimeler: Endodontik eğe, Bükme testi, Burulma testi, Sonlu elemanlar analizi

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Evaluation of the Biomechanical Properties of Endodontic Files with Different Taper Angles Using Finite Element Analysis

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Abstract

This study aims to evaluate the stress distribution of nickel-titanium (Ni-Ti) rotary tools with different conical angles during bending and torsion using finite element analysis (FEA). For the study, rotary file models with fixed taper angles of 0.02, 0.04, and 0.06 were modeled using Solidworks software. These models were transferred to ANSYS software. It was performed according to the ISO 3630-1 test specification using the FEA method to evaluate the flexibility and torsional stiffness of the files. According to the test results, the file system with a 0.02 taper angle showed higher flexibility when subjected to bending compared to the files with 0.04 and 0.06 taper angles. Regarding torsional resistance, the rotary file with a 0.06 taper angle demonstrated higher torsional resistance than the files with 0.02 and 0.04 taper angles. The geometry of the instrument affects the mechanical behavior (bending and torsional) of rotary files. Clinicians should be aware of the behavioral differences in rotary files and, in addition to following manufacturer instructions, should use the appropriate file according to the clinical situation.

Keywords: Endodontic file, Bending test, Torsional test, Finite element analysis

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1. Introduction

For a long time, Nickel-titanium (Ni-Ti) rotary file have been used for the mechanical preparation of teeth in root canal treatments [1]. Ni-Ti files exhibit superior flexibility when compared to stainless steel files. They also better preserve the anatomy of the root canal system [2]. However, during chemomechanical preparation processes, Ni-Ti files are significantly subjected to stress and strain. As a result of these stresses and strains, Ni-Ti rotary files can fracture within the root canal system [3]. Manufacturers have been modifying many features of Ni-Ti rotary files, such as design, geometry, and heat treatment, to enhance their clinical performance [4]. Currently, there are over 160 different Ni-Ti rotary file systems with various designs, kinematics, or heat treatments. Among these files, there are rotary file systems with the same apical size but with 0.02, 0.04, 0.06 taper angles [5-7].

Finite Element Analysis (FEA) is a numerical method used for evaluating the mechanical behaviors of materials used in endodontics [8]. It also allows for the simulation to be repeated without any risk by modifying the material properties as desired [9]. This makes it possible to observe the distribution of stress and strain that cannot be obtained under laboratory conditions and to monitor the mechanical behavior of the material [1, 4].

In the literature, there are many FEA studies on Ni-Ti rotary file systems [3, 4]. However, there is no study focusing solely on the variability of taper angle under ISO-3630-1 tests for a Ni-Ti rotary file. The purpose of this study is to comparatively evaluate three Ni-Ti rotary files, designed by us, with taper angles of 0.02, 0.04, 0.06 and a #30 apical size against the test limits of ISO 3630-1. The null hypothesis of this study is that files with different taper angles will produce different results against bending and torsional tests.

2. Materials and Method

The Ni-Ti endodontic rotary file models were designed to feature a commercially unavailable convex triangular and non-cutting tip design with concentric pitches, ISO #30 apical diameters, and conical angles of 0.02, 0.04, and 0.06 **(Figure1)**.

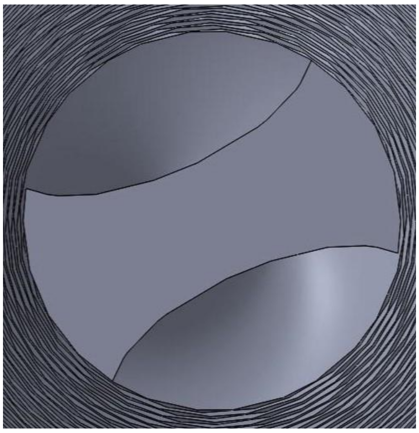

Figure1. Cross-sectional geometry of the designed Ni-Ti rotary file

These models were designed in 3D with a working length of 16 mm using Solidworks software (Dassault Systems SA, Concord, MA) and saved with a .prt extension **(Figure 2)**. The resulting Ni-Ti rotary file models were then saved with a Parasolid (.x_t) extension and made ready for use in ANSYS Workbench 2019 R1 software (ANSYS, Inc., Canonsburg, PA).

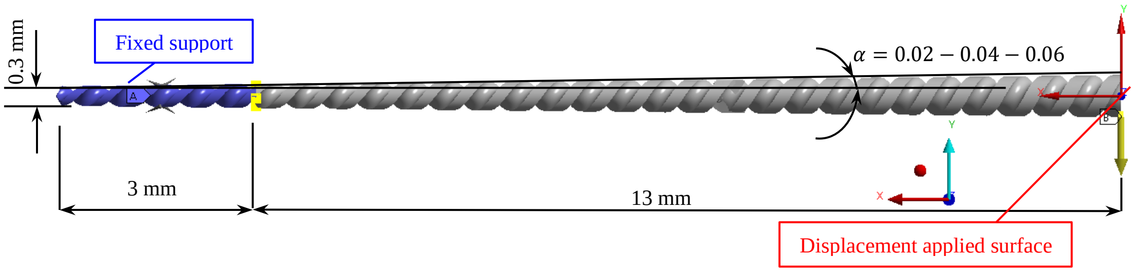

Figure 2. Ni-Ti endodontic rotary file model

For the properties of the rotary file, Ni-Ti material properties were selected in the ANSYS Workbench software. The mechanical properties used for this material are presented in Table 1 [1].

Table 1. Material properties of the Ni-Ti rotary file used in the analysis

Parameter	Description	Value
E	Young's modulus	60000 MPa
v	Poisson ratio	0.36
K	Bulk modulus	71429 MPa
G	Shear modulus	22059 MPa
σ_S^{AS}	Starting stress value for the forward phase transformation	520 MPa
σ_f^{AS}	Final stress value for the forward phase transformation	600 MPa
σ_S^{SA}	Starting stress value for the reverse phase transformation	300 MPa
σ_f^{SA}	Final stress value for the reverse phase transformation	200 MPa
$\bar{\varepsilon}_L$	Maximum residual strain	0.07 mm/mm
α	Parameter measuring the difference between material responses in tension and compression	0
E_S	Elastic modulus of the full martensite phase If 0 or undefined, the martensite and austenite phases share the same elastic modulus	60000 MPa

The created models were meshed using quadratic elements in the ANSYS Workbench software **(Figure 3)**. The models with 0.02, 0.04, 0.06 taper angles contain, respectively, 3701 nodes-1083 elements, 4694 nodes-1474 elements, and 7834 nodes-2150 elements. In this software, the axes of the Ni-Ti rotary files were positioned such that their axes were along the -x axis.

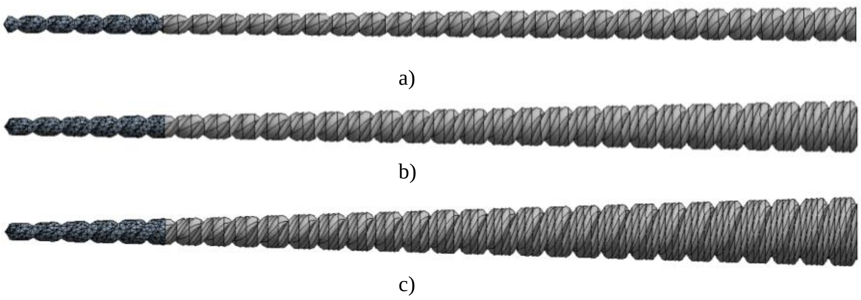

Figure 3. Mesh models created for analysis; a) α=0.02, b) α=0.04, c) α=0.06

The analyses of the Ni-Ti rotary file systems were conducted in ANSYS Workbench software according to ISO 3630-1 boundary conditions [10]. The boundary conditions for the bending test were achieved by applying fixed support at the apical end of the file as indicated in Figure 1, and at the coronal end, a displacement of 13 mm along the -y axis was given to provide a bending angle of 45 degrees. To achieve fixed support condition, the model was cut and separated 3 mm away from the apex in Solidworks software. In ANSYS Workbench software, a bonded connection boundary condition was applied to enable these two parts to move as a single piece. Free boundary conditions were applied to the coronal part of the model in the -x and -z axes **(Figure 4)**.

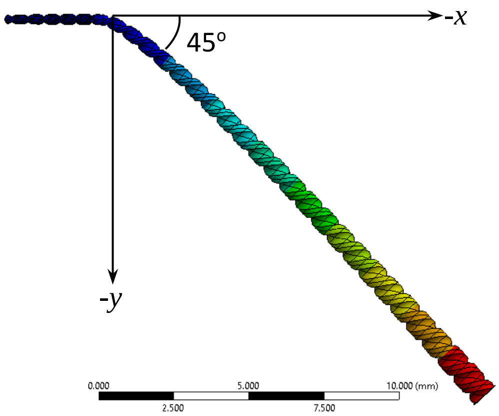

Figure 4. Application of 45-degree displacement to the Ni-Ti rotary file model in the -y axis

To observe the torsional behaviors of the created models, a boundary condition was applied as shown in **Figure 5**. Different from the bending test, a torque of 2 Nmm was applied from the coronal end of the model in the -x axis (Figure 5).

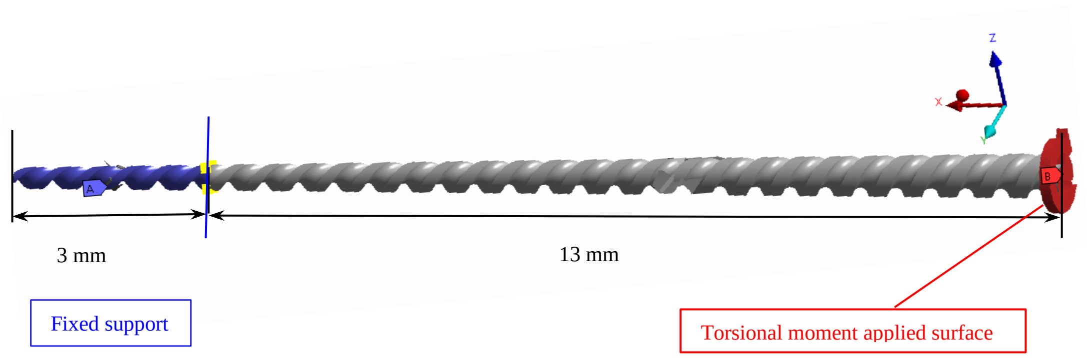

Figure 5. Application of rotational torque to the file model along the -x axis

3. Results and Discussion

3.1. Bending Test

Subjecting the file models to a 45-degree bending test showed similar behavior for each taper angle. The maximum von Mises stress value increased linearly up to about 10 degrees of bending, reaching ~700 MPa. For the taper angle α=0.02, this continued in a nearly constant manner up to ~45 degrees of bending, while for α=0.04, the stress increased to 1200 MPa after a bending angle of 35 degrees. However, for α=0.06, after about 20 degrees of bending, the stress increased linearly up to 45 degrees, reaching ~2000 MPa.

As the taper angle increased, the reaction bending moment also increased. With the increase in the bending angle, the reaction bending moment required to bend the rotary files was obtained in a manner similar to Figure 5. Up to ~10 degrees of bending, the reaction bending moment for each rotary file's taper angle increased linearly, being 0.6 N.mm for α=0.02, 1.5 N.mm for α=0.04, and 3 Nmm for α=0.06. After ~10 degrees of bending, the reaction bending moment continued to be constant for α=0.02, slightly increased to ~4 N.mm for α=0.04, and despite a decrease in the rate of increase, linearly rose to 9.5 N.mm for α=0.06.

When the models were forced to bend at an angle of 45 degrees, the behavior of the maximum von Mises stress corresponding to the bending angle was obtained in **Figure 6**, and the reaction bending moment corresponding to the bending angle was obtained in **Figure 7**.

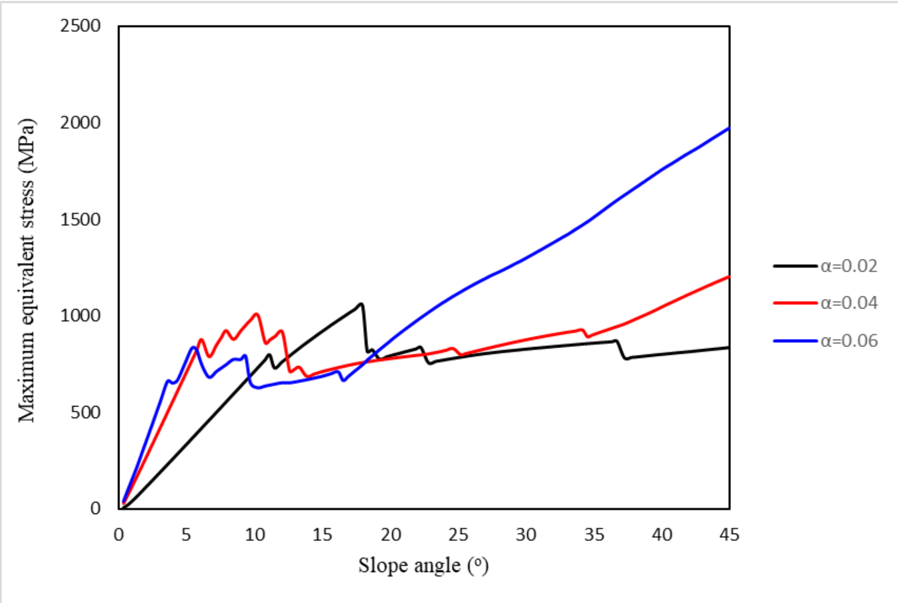

Figure 6. The effect of taper angle variation on bending angle- Maximum equivalent stress behavior

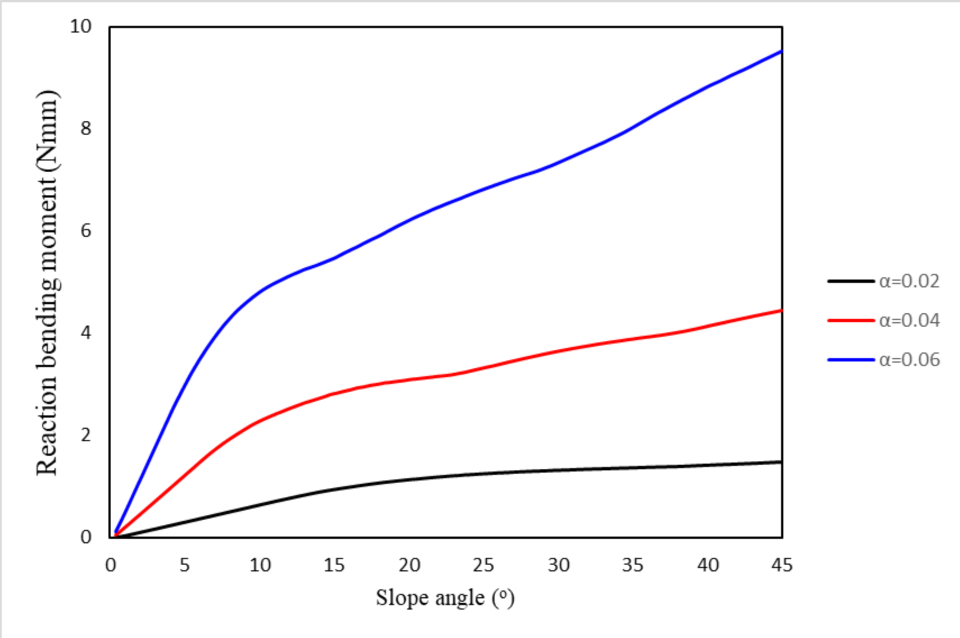

Figure 7. The effect of taper angle variation on bending angle - Reaction bending moment behavior

3.2. Torsion Test

The file models with taper angles of α=0.02, 0.04, 0.06 were fixed supported along a surface 3 mm from the apical end, and subsequently, a torque of 2 Nmm was applied to the surface on the coronal side. Applying a 2 Nmm moment to the Ni-Ti rotary file models showed similar behavior for each sample. As the Rotational Moment increased, the maximum equivalent stress increased linearly, found to be ~400 MPa for α=0.06, ~700 MPa for α=0.04, and ~1000 MPa for α=0.02. The maximum von Mises stress corresponding to the applied torque was obtained as shown in **Figure 8**.

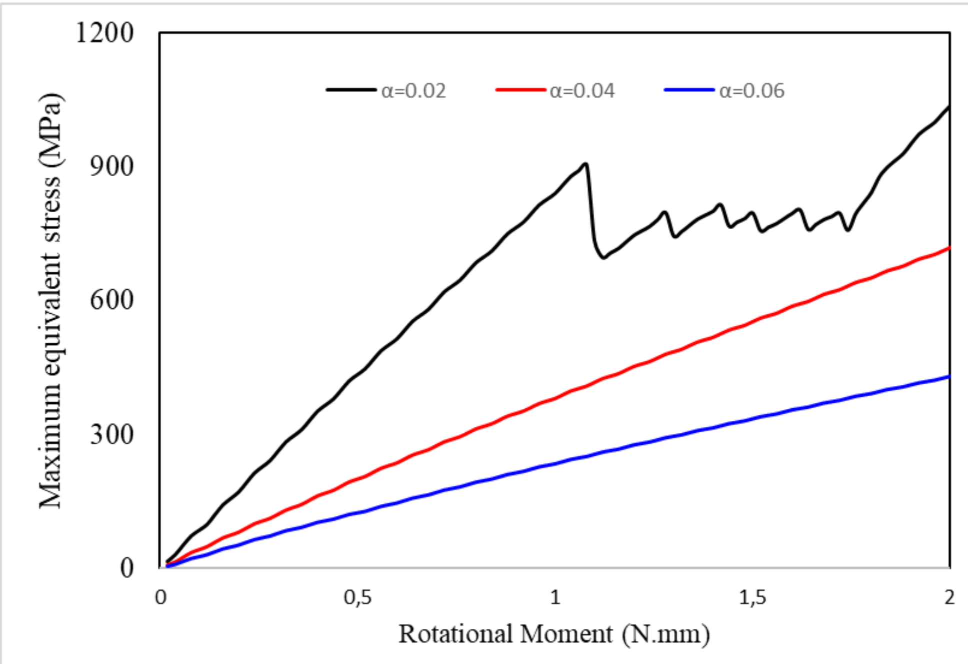

Figure 8. The effect of taper angle variation on Rotational Moment - Maximum equivalent stress behavior

In this study, the mechanical behaviors of endodontic rotary files with different taper angles during torsion and bending tests were examined using Finite Element Analysis (FEA). FEA is a numerical method capable of evaluating the mechanical behavior of an instrument, in addition to stress distribution during endodontic treatments [11-12]. FEA involves modeling a structure with loads and constraints to identify, analyze, and solve potential structural or performance issues. Moreover, FEA allows the application of different properties, such as alloy or design modifications, without causing any damage to the material. This situation enables the evaluation of the mechanical properties of rotary file systems used in endodontics by reducing time and cost [13-14]. We also used FEA in our study due to its advantages.

In superelastic material behavior, when subjected to a tensile test, the material undergoes a certain amount of deformation but recovers its shape along a different path once the force is removed [3]. Additionally, different thermomechanical treatments are applied to endodontic rotary files [15, 16]. However, the study focused on the effect of different taper angles on bending and torsional rigidity, so the ultimate differences in material properties were disregarded. This study was conducted according to ISO 3630-1 boundary conditions [4, 14, 17] and is similar to other studies evaluated with FEA. The bending and torsional properties of the files were assessed. FEA results under bending conditions show that the rotary file with a 0.02 taper angle is more flexible than those with 0.04 and 0.06 taper angles. As a result of this difference, the null hypothesis in our study was accepted. This difference can be explained by the smaller cross-sectional structure in the apical 3 mm portion of the file with a 0.02 angle. Based on these results, rotary files with lower taper angles should be used in shaping curved root canal systems. In similar clinical conditions, a file with a 0.06 taper angle would need to apply more force to the walls of the root canal to achieve the same degree of bending. This is thought to potentially cause complications such as perforations or the formation of zips in the apical region of the root canal system in teeth with curvature. However, when rotary files are placed within the root canal system, the boundary conditions can change due to varying contact points.

In the torsion test, the effect of the tool connection was simulated by fixing the instruments 3 mm from the file tip and applying a torque of 2 Nmm. According to the test results, the rotary file system with a 0.06 taper had a lower angular rotation value compared to the others. The increase in cross-section in this test reduced the stress due to an increase in the file's inertia. This also reflected in the stress behavior. In this study, the bending test was performed on the xz axis. In tests to be performed on different axes, different results can be obtained due to the pitch structure of the file. In addition the results obtained in this study are consistent with the findings of studies showing that torsional rigidity depends on the cross-sectional geometry [11, 18, 19]. Additionally, the stress levels in tools under torsion cannot be predicted solely by stiffness responses. The combination of factors such as the cross-sectional geometry of the files, their mechanical properties, the location of stress application, and the location where deformation is measured, influences the stress [2, 20].

4. Conclusion

Clinicians might prefer samples with a higher taper angle considering the stress that rotary files will be subjected to, based on their bending and torsional behavior. However, it is important to take into account that increasing the taper angle could make the movement of the file more challenging.

5. Author Contribution Statement

Mehmet Eskibağlar: Conceptualization, Methodology, Data curation, Writing-Original draft preparation; Serkan Erdem: Visualization, Software, Validation, Investigation, Writing-Reviewing and Editing

6. Ethics Committee Approval and Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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