ORIGINAL ARTICLE

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Evaluation of biomechanical properties of endodontic files with different pitch by finite element analysis

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Purpose: The purpose of this study was to evaluate the stress distribution of endodontic nickel-titanium (Ni-Ti) rotary files with different pitches in bending and torsion tests using finite element analysis (FEA).

Methods: Finite element models of superelastic Ni-Ti endodontic rotary instrument files with three different pitches (12, 15, and 18) were created using SolidWorks software. All endodontic files were modeled with the same length, apical diameter, and cross-sectional geometry. These models were transferred to ANSYS software for analysis. Tests to evaluate the flexibility and torsional stiffness of the files were performed using the FEA method, according to the ISO 3630-1 specification. The results obtained were calculated using the von Mises stress.

Results: The stiffness and maximum stress decreased as the pitch value increased. According to the test results, the 18 pitch file system exhibited higher flexibility than the 12 pitch and 15 pitch file systems when subjected to bending. In terms of torsional resistance, the 12 pitch rotary file showed higher torsional resistance than the 15 pitch and 18 pitch endodontic files.

Conclusion: Clinicians should be aware of the geometric differences in rotary files and use the appropriate file for clinical situations in addition to the manufacturer's instructions.

Keywords: Bending test; endodontic rotary file; finite element analysis; pitch; torsion test.

Introduction

Nickel-titanium (Ni-Ti) rotary instruments are widely used in endodontics. Ni-Ti rotary instruments allow for easy and quick preparation of the root canal system while providing more successful treatment than hand instruments (1). Ni-Ti instruments have greater flexibility and improved cutting ability compared to stainless steel instruments (2). Despite the advantages of Ni-Ti rotary file systems, these instruments are subject to fracture due to cyclic and torsional fatigue (2,3).

The two most important properties that affect the performance of Ni-Ti rotary instruments in clinical use are torsional stiffness and bending flexibility (4,5). Although there are many test methods in which these properties are evaluated, the ISO 3630-1 specification is frequently used in these studies. In this specification, the bending test was performed by holding the file 3 mm from the tip and bending it 45°. The torsion test was performed by holding the file 3 mm from the tip and rotating the shaft clockwise (6). Enhancing the geometric designs leads to better ef-

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ficiency of endodontic files. The influence of various geometric designs on the efficiency of endodontic files has been primarily studied through the analysis of the cyclic fatigue resistance of instruments in endodontic literature (7,8). However, the cyclic fatigue test does not assess geometric parameters such as pitch and apical diameter, which are associated with the bending and torsional behavior of instruments (9). The mechanical behavior and stress distributions of Ni-Ti rotary instruments subjected to various conditions can be determined mathematically using finite element analysis (10).

The purpose of this study is to evaluate the biomechanical properties of the variable pitch values of the Ni-Ti rotary file system, the design of which belongs to us, under ISO 3630-1 boundary conditions.

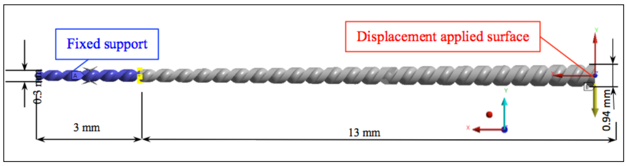

Fig. 1. Sample boundary condition and dimensioned Ni-Ti file model.

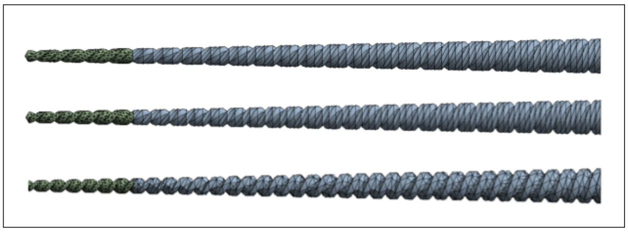

Fig. 2. Mesh structure of the analysed endodontic file **(a)** 12 pitch, **(b)** 15 pitch, **(c)** 18 pitch.

Materials and Methods

Ni-Ti rotary instrument files, which were not commercially available, were designed with convex triangular cross-section, ISO #30 apical diameter, 0.04 taper angle, and 12, 15, and 18 pitch. These models were 3D modeled using SolidWorks software (Dassault Systems SA, Concord, MA, USA) with a working length of 16 mm and were saved with *.prt extensions (Fig. 1). The resulting Ni-Ti rotary file models were saved in Parasolid (*.x_t) extension and prepared for use in the ANSYS Workbench 2019 R1 software (ANSYS, Inc., Canonsburg, PA, USA).

The Ni-Ti material properties were selected in the Ansys Workbench software for the properties of the Ni-Ti rotary file to be used in the ISO-3630-1 tests (11). The mechanical properties of the materials are listed in Table 1 (12).

In ANSYS Workbench software, the Ni-Ti file axes were positioned using the -x axis. The Ni-Ti rotary file models were meshed using quadratic elements (Fig. 2). As a result of the meshing process, the 12-15-18 pitch models contained 4997 node-1518 elements, 4694 node-1474 elements, and 7379 node-3795 elements.

Analyses of the Ni-Ti rotating file systems were performed using the ANSYS Workbench software according to the ISO 3630-1 boundary conditions (10). The bending test boundary conditions were established by providing fixed support on the apical side of the file and 13 mm displacement on the coronal side to provide a bending angle of 45° along the -y axis, as shown in Figure 1. To create the fixed support condition, the model was cut 3 mm from the apical side using the SolidWorks software and divided into two parts. In ANSYS Workbench software, a bonded connection boundary condition was applied to allow the two parts to move as one piece. A free boundary condition was applied to the coronal side of the model along the -x and -z axes (Fig. 3).

To observe the torsional behavior of the models, a boundary condition was applied as shown in Figure 4. Unlike in

Table 1. Material properties for 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

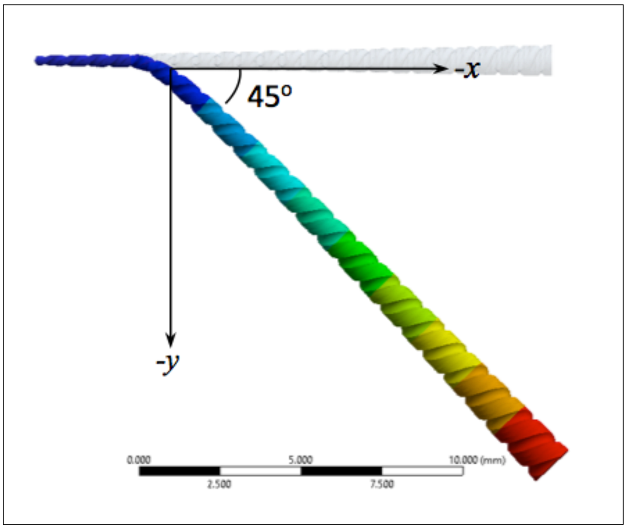

Fig. 3. 45° displacement in -y axis to the endodontic file model.

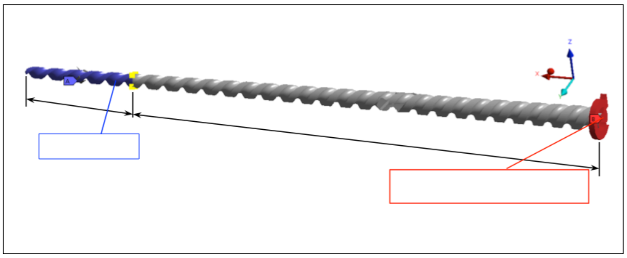

Fig. 4. Application of the rotation moment along the -x axis to the endodontic file model.

the bending test, a torque of 2 Nmm was applied on the -x axis from the coronal side of the model.

Results

Bending Test

In accordance with the ISO 3630-1 boundary condition, a fixed support of 3 mm length was applied to the apical end of the file on rotary file models with different pitch values. The Ni-Ti rotary file was then forced to bend at a 45° angle to the coronal side of the file. The maximum von Mises (vM) stress occurred in a similar pattern for the Ni-Ti rotary files subjected to bending. The maximum vM stress in all Ni-Ti rotary files was 600-900 MPa with a linear increase up to ~10° bending angle and remained constant up to ~35° bending angle. When the bending angle was increased to 45°, the stress again increased linearly and was ~1500 MPa for the 12 pitch Ni-Ti rotary file, ~1200 MPa for the 15 pitch Ni-Ti rotary file, and ~1000 MPa for the 18 pitch Ni-Ti rotary file.

The reaction bending moment behavior of the Ni-Ti rotary files for 45° bending was similar for each file. Reaction bending moments for ~10°-15° bending were obtained as

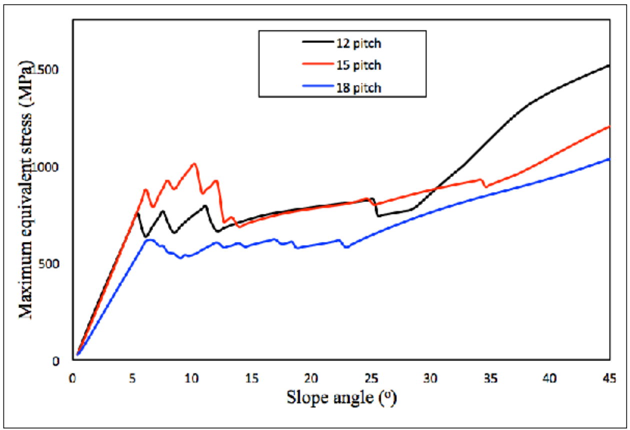

Fig. 5. Effect of change in pitch on bending angle behaviour- maximum equivalent stress.

3 Nmm for 12 pitch, 2.5 Nmm for 15 pitch, and 2 Nmm for 18 pitch files with a linear increase. When the bending angle was increased by 45°, the increase in reaction bending moment was again linear, but the increase decreased and was obtained as ~5.5 Nmm for 12 pitch, ~4.5 Nmm for 15 pitch, and 3.5 Nmm for 18 pitch.

The maximum vM stress versus bending angle is shown in Figure 5, and the reaction bending moment versus bending angle is shown in Figure 6.

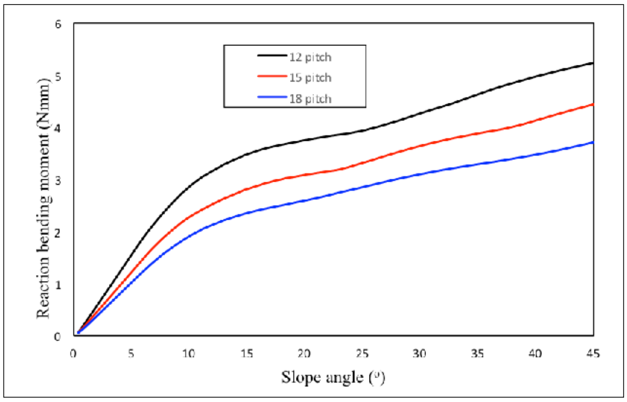

Fig. 6. Effect of change in pitch on bending angle- Reaction bending moment behavior.

Torsion Test

A torque of 2 Nmm was applied to the Ni-Ti rotary file models in accordance with the ISO 3630-1 boundary conditions. As a result of this test, the maximum vM stress values of the 12 and 15 pitch models were obtained as ~720 MPa, with a linear increase. In the 18 pitch file, the maximum vM stress was obtained as ~600 MPa with a linear increase at 1.6 Nmm torque and was then found to be constant. Figure 7 shows the vM stress values against the torsion test, where the red areas represent the damage stresses. The highest stress was localized on the outer sur-

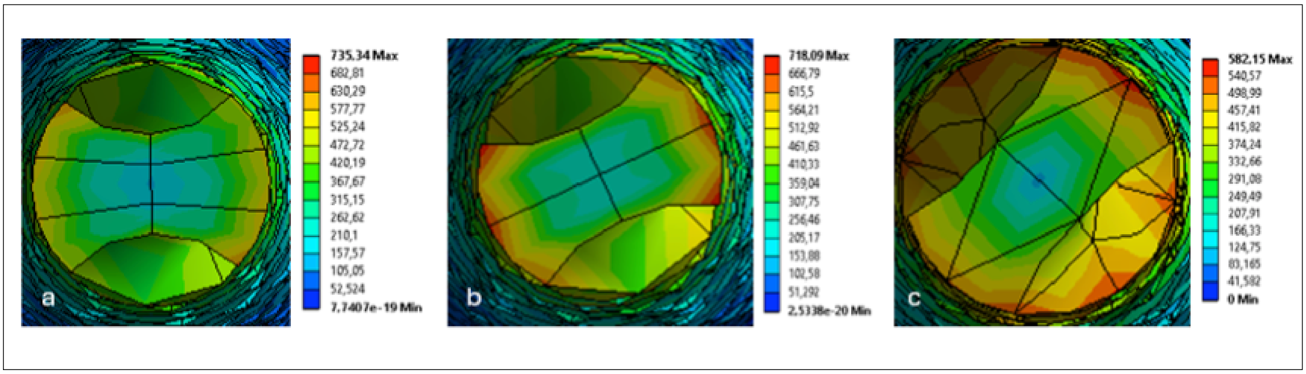

Fig. 7. Max vM stress according to the number of pitches in torsion test a) 12 pitch, b) 15 pitch, c) 18 pitch.

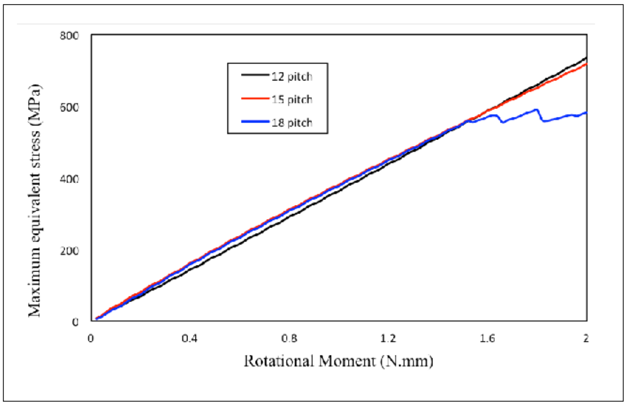

Fig. 8. Effect of pitch on torque- maximum equivalent stress behavior.

face of the Ni-Ti file. The maximum vM stress is obtained as a function of the applied torque, as shown in Figure 8.

Discussion

The performance of Ni-Ti rotary instruments with a variable pitch was evaluated under bending and torsion loads using FEA analysis in this study. FEA allows for the assessment of the impact of different geometrical parameters on the mechanical properties of materials through computational processing (13). This method enables the calculation of stress distributions and concentrations, minimizes uncontrollable variables, and ensures the repeatability of the test conditions for analysis (14,15). Owing to its effectiveness in analyzing the stresses that arise during the use of Ni-Ti rotary files, FEA is commonly utilized in the field of endodontics (16,17). Therefore, we employed the FEA method to assess the mechanical performance of Ni-Ti rotary files in our study.

The Ni-Ti rotary file systems analyzed in this study were selected as superelastic materials. In this material behavior, when the superelastic material is subjected to a tensile test, it undergoes a certain deformation. However, when the force on it is removed, it returns the deformation by following a different path (18). In addition, various thermomechanical processes have been applied to Ni-Ti rotary file systems to increase their strength (19,20).

However, because this study evaluated the effect of different pitches on bending and torsional stiffness, differences in the material properties of the Ni-Ti rotary files were not considered.

The helical flute angle is formed by the cutting edge and a cross-section perpendicular to the long axis of the file, and the pitch is the distance between the two cutting edges in the lateral view (21). The pitch of an instrument is significant because it influences flexibility and cutting efficiency (22). A decrease in the value of pitch and an increase in the number of flutes increase the working cutting edge length of a file, which improves the cutting efficiency of the instrument, increases the bending stiffness, and reduces stress (3). Instruments with increased pitch allow for debris removal and flexibility; however, the risk of torsional failure increases because of the distribution of high stress (23). A Ni-Ti rotary file system generally has 5-15 pitch (3). In previous studies that used finite element models to investigate the effect of pitch length, a short, decreased pitch (increasing threads) reduced the stiffness of the files (3,22). Our results are also supported by previous studies that used finite element models in which the short pitch had a higher torsional fracture resistance (3,22,23). In addition, short pitch files may be preferred when high flexibility is expected from files in clinical practice.

Changes in pitch affect Ni-Ti rotary files with different cross-sectional shapes. Instruments with square cross-sections were the least affected, whereas those with rectangular cross-sections were the most affected by the pitch value. The different cross-sections of the Ni-Ti rotary file affected the results (21). Our study changing the pitch value may have affected the results by causing the cross-sectional geometry to differ between files. Because our study focused on pitch variability, cross-sectional geometry was ignored. This is one of the limitations of this study.

However, in models with convex triangular cross-sections, the maximum stress occurred at the periphery (or border) of the cross-sections and was often located near the base or “bottom” of the flute. One of the factors that may affect these stresses is that only the working part of the file was modeled in our study. Testing the file together with the shaft may be one of the factors affecting the results of this study. This is one of the limitations of this study.

The tests in this study were performed according to the boundary conditions of ISO 3630-1 in order to standardize the Ni-Ti rotary file studies evaluated by FEA (6,24,25). Increasing the pitch value of the Ni-Ti rotary files of the same length resulted in more material being removed from the Ni-Ti rotary file. In the bending test, increasing the pitch value of the Ni-Ti rotary files led to a decrease in the force required to bend the files. Consequently, the maximum vM stress decreased as the pitch increased. The results obtained in our study are consistent with those of similar studies (8,23). Furthermore, based on the results obtained in our study, it is recommended to use rotary files with a higher pitch value to shape curved root canal systems (8). From a clinical perspective, a 12-pitch file may exert more force on the root canal walls because of its higher stiffness causing complications such as perforation or zip formation in the root canal system. However, when rotary files are placed in the root canal system, the boundary conditions may change because of the changes in the contact points on the root canal walls.

In the torsion test, the effect of the instrument connection was simulated by fixing the endodontic rotary file 3 mm from the apical end and applying a torque of 2 Nmm. According to the test results, the torsional moment of the 18 pitch rotary file system was lower than those of the others. Increasing the pitch reduces the cross-sectional area for the same length, which reduces the inertia and therefore the stress in the file. This is also reflected in the stress behavior. These results are consistent with those of other studies showing that torsional stiffness is dependent on cross-sectional geometry (26,27). In addition, the stress levels in tools under torsion cannot be predicted from the stiffness response alone. A combination of factors such as the cross-sectional geometry of the files, their mechanical properties, where the stress is applied and where the deformation is measured, will influence the stress (28).

Conclusion

For biomechanical preparation of the root canal system, clinicians may prefer a rotary file system with a higher pitch value, depending on the bending and torsional behavior, considering the stress to which the Ni-Ti rotary files will be subjected. In addition, it should be noted that the low pitch value in the preferred Ni-Ti rotary file system may make file movement more difficult.

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