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Influence of nickel-titanium rotary systems with varying cross-sectional, pitch, and rotational speed on deflection and cyclic fatigue: a finite element analysis study

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Abstract. The effectiveness of endodontic file preparation depends, among others, on the material, geometric shape, and the drive system. This study aimed to analyze the effect of cross-sectional, pitch, and rotational speed on cyclic fatigue and deflection of NiTi files using finite element analyses. A total of 18 NiTi endodontic rotary instruments ProTaper Gold F2 #25.08 and Hyflex CM #25.04 (n=9) modeling were designed using Autodesk software. Subjects were divided into two groups, the design group of square and convex triangles. Static simulation was then carried out to each group with force on the instrument's tip by 1N, 2N, and 3N. The file's cycling fatigue was analyzed at rotating speeds of 200 rpm, 300 rpm, and 400. The data were analyzed by using the three-way Analysis of variance (ANOVA) test followed by LSD ($p < 0.05$). The results showed the cross-sectional shape and force effect on the deflection value and cyclic fatigue received by the endodontic files ($p < 0.05$). The convex triangle design presented the lowest cyclic fatigue than square. The convex triangular cross-section design showed a higher deflection value than the square cross-section design.

1 Introduction

Dental caries have a significant consequence on the quality of human life. The untreated dental caries and associated infection may end as pulp necrosis and apical pathology [1]. Root canal treatment (RCT) treats the tooth's infected pulp, intended to eliminate infection and protect the decontaminated tooth from future microbial invasion. Successful RCT is based on good debridement, disinfection, and sealing of the whole root canal system [2]. Adequate cleanup and constructive become the essential elements for successful treatment by eliminating microorganisms through mechanical debridement. This process is intended to produce a good shape that provides efficient disinfection using endodontic irrigation solutions and optimize the geometry of the root canal [3, 4].

Presently, NiTi rotary instrument driven by a machine is the most widely used in the root canal preparation method. The preparation results are more consistent and faster, requiring less preparation time than preparation by using manual instruments [5]. However, the rotary mechanism may cause dentine fracture due to the friction between the file and root canal walls. And file and the tool can make dentine defects [6].

Moreover, the rotary instrument is considered to be prone to fracture in clinical use during chemo-mechanical preparation. Instrument fractures are typically thought to be induced by, among other things, excessive torsion forces, bending failure, or failure in the fatigue cycle. The leading precipitate of NiTi device failure is the bending fatigue cycle that occurs when the device rotates in a root canal with a curve shape [7, 9].

The cyclic fatigue fracture arises as a result of metal fatigue. There is no binding of the file in the canal but rather free rotation in a curvature, which induces compression/tension cycles at the maximum flexure point until the occurrence of the fracture. Instrument fracture is associated with rotational speed, which affects the cyclic fatigue value of an instrument [8, 9]. The failure of torque on an instrument will generate an angle due to a change in deformation. This deformation is referred to as deflection [10].

The greater the deflection angle formed before the instrument fracture owing to torsion, the higher the tolerance to deformation at the plastic and elastic stages of the instrument. The deflection of the file affected the flexibility of the file. Sufficient flexibility helps reduce bending stresses and reduces the risk of failure due to bending fatigue. Those properties are the main characteristics of the instrument, reducing

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iatrogenic failure to produce canal transport, increasing preparation efficiency, and increasing safety in root canal treatment [6, 11].

Many changes in endodontic files design have been observed during the past few years, with innovations in device design, surface, thermal manipulation for NiTi alloys, integrating and blending new action schemes to handle device systems [12]. A controlled memory wire (CM wire), memory wire (M wire), and electrical discharge machining (EDM) were produced by a thermomechanical technique. That technique optimizes the mechanical and microstructure properties of NiTi alloy [13, 15]. One rotary instrument that uses M-wire material is Protaper Next™, while Protaper Gold™ and Hyflex CM™ are instruments made from CM wire [14, 15]. Both ProTaper Gold and Hyflex have the advantage of 300% more resistance to cyclic fatigue than NiTi files. They can follow the shape of a root canal very similarly, thereby reducing the risk of lodging, transportation, and perforation [16, 17].

With the rapid development of computer science and technology, a new simulation and design appeared using computational methods. Simulating a treatment using a specific program on the computer is called the *in-silico* approach [18, 19]. One of the tools of this approach used to simulate the design to help study geometry is the finite element method (FEM). Further, the FEM approach is solved by using Autodesk® Inventor, ABAQUS®, and ANSYS® software.

This study objectives to examine the influence of cross-sectional, pitch, and rotational speed on cyclic fatigue and deflection of NiTi files using the finite element method.

2 Materials and Methods

This study was accepted and approved by Commission for Dental Ethics at Universitas Gadjah Mada, Yogyakarta, Number 00467/KKEP/FKG-UGM/EC/ 2020. Two types of endodontic files, namely ProTaper Gold F2 (PTG) 25.08 with a base diameter of 1.2 mm; taper 0.08; pitch 10 and Hyflex CM 25.04 (HCM) with a base diameter of 1.2 mm; taper 0.04; pitch 10 were selected. The cross-sectional shape of HCM is square, while PTG is a convex triangle. Those two files were scanned 3D scanning with the μ-CT scanner Sky Scan 1173 High-Energy micro-CT, followed by 3 D file modeling through the Autodesk Inventor 2020 application. In silico analysis was performed to investigate the deflection and cyclic fatigue of both files.

The files were modeled using Computer-Aided Design (CAD) software. The Autodesk Inventor Professional 2020 software was carried out to change the number of pitches from the manufacturer. Instead of the original number of pitches, the files were modified by changing the number of pitches +1 and -1.

Then, all models were imported to the ANSYS Structural 18.2 application, where the static load simulation was computed. The original physical properties of those two files were analyzed in the ANSYS application and entered as the file's physical properties data. Subsequently, the selected data was imported through the geometry option import with extension (.stp). Later, a dominant hex mesh was created for computation and computer reading with a body sizing 0.1 mm. The next step was to determine the load and perform force simulation (1 N, 2N, and 3N). After that, the total deformation solution was selected for the output results. The calculation process in the simulation was carried out three times. The deflection of endodontic files was presented in millimeters (mm). The cyclic fatigue values were obtained in NCF units and then divided by the variable rotational speed that has an effect. The final cyclic fatigue value was obtained in minutes.

3 Results

3.1 Deflection

Means and standard deviations of the deflection value of two continuous NiTi files (mm) are presented in Table 1. The highest deflection was revealed by the file loaded with 3 N force, which has a convex triangular cross-section with a +1 pitch. While the lowest value was obtained by the file loaded with 1 N force, it has a square cross-section with a -1 pitch.

Table 1. The mean and standard deviation of the deflection values of two continuous NiTi files (mm).

Load	Cross Sectional							Mean	Standard Deviation
		ProTaper Gold F2 (convex triangle)			HCM 25.04 (square)				
		Number of *Pitch*			Number of *Pitch*				
		Real	-1	+1	Real	- 1	+ 1		
1 N	Sample 1	6,89	6,86	6,93	5,290	5,284	5,305	6,093	0,877
	Sample 2	6,89	6,86	6,93	5,290	5,284	5,305		
	Sample 3	6,89	6,86	6,93	5,290	5,284	5,305		
2 N	Sample 1	9,92	9,90	9,97	8,472	8,463	8,481	9,201	0,799
	Sample 2	9,92	9,90	9,97	8,472	8,463	8,481		
	Sample 3	9,92	9,90	9,97	8,472	8,463	8,481		
3 N	Sample 1	11,90	11,89	11,95	10,55	10,543	10,553	11,231	0,748
	Sample 2	11,90	11,89	11,95	10,55	10,543	10,553		
	Sample 3	11,90	11,89	11,95	10,55	10,543	10,553		
Mean		9,570	9,550	9,617	8,104	8,097	8,113	8,842	
Standard Deviation		2,523	2,533	2,529	2,649	2,6484	2,6435		2,303

A three-way analysis of variance (ANOVA) with the Randomized Complete Block Design (RCBD) design was used. It demonstrated that load and cross-sectional shape significantly influenced the deflection of the file ($p<0.05$). Nevertheless, there was no significant difference among the original, the variation of -1 and +1 of pitch number (Table 2).

Table 2. The deflection value with three-way ANOVA test.

Deflection Value	Sum of Squares	Degree of freedom	Mean Square	F	Probability (p)
Load	80.352	2	40.176	10849.391	.000*
Cross Sectional	9.782	1	9.782	2641.562	.000*
Pitch	.005	2	.003	.724	.505
Total	90.139	5	-	-	-

* = significantly different ($p <0.05$)

3.2 Cyclic fatigue

The value of cyclic fatigue was measured based on the finite element method, simulated on ANSYS Structural 18.2 software. The research was conducted three times with simulations on two continuous NiTi endodontic rotary instruments. The mean and standard deviation of cyclic fatigue of two continuous NiTi endodontic rotary devices in minutes are presented in Table 3.

Table 3. Mean values and standard deviation of cyclic fatigue of two continuous NiTi endodontic rotary instruments (minutes).

Group	n	Mean ± Standard Deviation
Rotational speed	6	3,1783 ± 1,4377
Cross-sectional	6	3,1780 ± 1,6910
Pitch	6	3,1787 ± 1,1207
Total	18	

The data is further analyzed by a three-way analysis of variance (ANOVA) with a randomized complete block design (RCBD. There are significant disparities in the value of cyclic fatigue between the two continuous NiTi endodontic rotary instruments with a variety of rotational speeds and cross-sectional shapes ($p<0.05$) (Table 2). On the contrary, the variation of the pitcher (9, 10, and 11 pieces) does not influence the cyclic fatigue ($p>0.05$). The results of the mean values of the three-way ANOVA descriptive test were used to determine the value of cyclic fatigue at different rotational speeds and cross-sectional shapes.

Table 4. The cyclic fatigue value with a three-way ANOVA test.

Cyclic fatigue	Total square	Degree of freedom	Mean square	F	Probability (p)
Rotational speed	15,079	2	7,540	10,579	0,002*
Cross sectional	25,014	1	25,014	35,097	0,000*
Pitch	0,017	2	0,008	0,012	0,988
Total	40,110	5	-	-	-

4 Discussion

The design of the endodontic file considerably influences the success of cleaning and shaping. Deflection and cyclic fatigue are the properties that are important to gain a satisfactory function of the files. This study examines those two properties through an in silico study by computer simulation. Based on the data obtained, it is evident that the greater the loading value, the greater the deflection value. The highest deflection value is revealed when the 3 N forces are applied. Following the previous study, the greater loading applied to the instrument end, the value and the deflection angle of the instrument will increase, both of which will also affect the flexibility of the file. The notion of flexibility supports this file. The elastic bending force is applied to endodontic instruments at its end. The load is applied in the direction perpendicular to its long axis [11]. The flexible rotary file was made by nickel-titanium and had a greater deflection angle [10]. Sakaguchi and Powers' formula states that deformation is proportional to load [13]. Thus, it can be concluded that the greater the load, the greater deformation or deflection. This behavior affects the instrument's flexibility, whereas the instrument's shape is not deformed at the lower elastic limit [20]. The limit is recorded as the elasticity value before the device is broken [11].

In the present study, the size and geometric changes influence the instrument's mechanical properties [15] without modifying the pitches number. There are two types of in silico study designs of root canal preparation, i.e., static and dynamic motion. The limitation of the static study is the absence of pecking motion (movement up and down during root canal preparation). However, the dynamic motion also does not show the actual results of the clinical activity [21]. This is inconsistent with the statement that decreasing the pitch (shorter distance and adding the number of threads) of the instrument increases the flexibility of the instrument [22].

The reductions of pitch distance also impact the addition of the cutting edge, thereby effectively increasing the length of the instrument. The longer the instrument, the more flexible it is due to the less pressure required to bend [23]. Previous researchers stated that the number of flutes (as the unit length of the pitch forming) has little effect on instrument bending [24].

This examination presents a similar result to the past study that the triangular section shape has higher flexibility than a square design with the same taper conditions and instrument diameter [23]. A convex triangle reveals a larger deflection value compared with the square cross-section. This shape reduces the contact point between the cross-sectional area of the file and the root canal wall, thus increasing the flexibility of the file [20]. Based on the analysis in the study, triangular cross-sections reduce flexural stiffness and stress by increasing the number of threads or reducing pitch. At the same time, square sections, composed of high cross-sectional and center-core areas, produce higher stiffness and stress against deflection at a 5mm tooltip. In conclusion, a wider area of the cross-sectional shape has a higher level of stiffness.

In a clinical situation, the instrument's safety should be one of the considerations in instrument choice. The design and properties of the rotary file material are important factors that influence the safety of the device. A flexible file may minimize the risk of inadequate or improper root canal shape, ledges, transport, and perforation, particularly in the complex or curved root canals [11]. Their geometric configuration considerably influences the mechanical action of endodontic instruments. Flexibility is required to negotiate acute curvatures with minimal canal transport, but it is still stiff enough to withstand the stresses when entering narrow canals [23].

In the results of the present study, there was an effect of cyclic fatigue on the continuous NiTi rotary endodontic file at a different cross-sectional and rotational speed. The research data obtained that the cyclic fatigue of the NiTi rotary endodontic file decreased, along with the increase in rotational speed in the two cross-sectional. The instrument reaches the fatigue point faster when used at higher speeds. A higher rotating speed can result in higher stress and frictional torque on the tool, causing the device to experience more compression stress cycles [21, 22].

More compression stress cycles result in a faster time for the device to reach its fatigue point.

A Rotary instrument was operated at a speed that minimizes fracture incidence while maintaining the device's efficiency. A higher rotational speed will make the instrument more susceptible to fracture than a lower rotational speed [23]. The fracture is due to increased stress strain and a reduced time for stress relaxation [24].

In addition, the Post Hoc statistical analysis on the variable rotational speed shows that the instrument driven using a 200 rpm rotating speed reveals the higher cyclic fatigue than those the file that turns in a 300 rpm and 400 rpm speed. Cyclic fatigue is related to the time when a file reaches the fatigue point.

Thus, the instrument that rotates at 200 rpm speed may prolong its lifespan. Despite rotating speed, cyclic fatigue is also affected by cross-section. The square cross-section exhibits more significant cyclic fatigue than the convex triangle. It may be due to the shape of the square section having a thinner core mass than the triangular cross-section, reducing the stress on the file during its spin in the root canal.

The simulation of pitch number variation proves that the pitch does not influence cyclic fatigue. It could be that adding or reducing 1 pitch number is not enough to reduce the file's stiffness since the length of the file does not change significantly.

5 Conclusion

The cross-sectional and rotational speed influence the cyclic fatigue value of the endodontic rotary file made from nickel-titanium was investigated. The results showed that the number of pitches did not affect the cyclic fatigue value or the deflection value of the rotating file. Finally, a convex triangle section will play an essential role in a geometric design to get a more excellent deflection value.

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References

1. M.P. Silva, M.V. Vettore, M.A.B. Rebelo, J.M. Vieira, A.P.C.Q Herkrath, A.C. Queiroz, F.J. Herkrath, J.V. Pereira, Caries. Res. **54,** 2 (2020).
2. L.H. Berman, K.M. Hargreaves, Clinical Endodontics in Cohen's Pathways of the Pulp 12th ed. Elsevier (2020).
3. M.I. El-Anwar, S.A. Yousief, E.M. Kataia, El-T.M.A. Wahab, Braz. Dent. J. **27,** 5 (2016).
4. M. Leski, M. Radwanski, H. Paulicka, Dent. Med. Probl. **52**, 1 (2011).
5. Y. Shen, H.M. Zhou, Y.F. Zheng, L. Campbell, B. Peng, M. Haapasalo, J. Endod. **37, 11** (2011).
6. J. Zupanc, N. Vahdat-Pajouh, E. Schafer, Int. Endod. J. **51**, 10 (2018)
7. P. Jain, Current Therapy in Endodontics (Blackwell, Dubai, 2016).
8. K.S. Shim, S. Oh, K. Kum, Y.C. Kim, K.K. Jee, S.W. Chang, Mechanical and Metallurgical Properties of Various Nickel-Titanium Rotary Instruments, Biomed Res. Int. (2017).
9. Y. Fukumori, M. Sishijyo, D. Tokita, K. Miyara, A. Ebihara, T. Okiji, Comparative analysis of mechanical properties of differently tapered titanium endodontic rotary instruments, Dent. Mater. J. **37**, 4 (2018).
10. R. Caicedo, S.J. Clark, S.J. Endod. Prac. **4,** 6 (2012).
11. G. Gambarini, L. Testarelli, V. Milana, R. Pecci, R. Bedini, G. Pongione, R. Gerosa, M. Luca, Ann. Is. Super. Sanita. I. **45,** 4 (2009).
12. A. Scattina, M. Alovisi, D.S. Paolino, D. Pasqualini, N. Scotti, G. Chiandussi, E. Berutti, J. Endod. **41,** 11 (2015).
13. L.A. Santos, J. Lopez, E.N. Casas, M.G.A. Bahia, V.S. Buono, Mater. Sci. Eng. C. Mater. Biol. Appl. **37** (2014).
14. T.M. Hamdy, M. Galal, A.G. Ismail, R.M. Abdelraouf, J. Med. Sci. **7,** 21 (2019).
15. W.A. Khalil, Z.S. Natto, Restor. Dent. Endod. **44,** 2 (2019).
16. S.H. Baek, C.J. Lee, A. Versluis, B.M. Kim, W. Lee, H.C. Kim. J. Endod. **37,** 9 (2011).
17. A. Versluis, H.C. Kim, W. Lee, B.M. Kim, C.J. Lee. J Endod. **38,** 10 (2012).
18. E. Schafer, J. Tepel. J. Endod. **27,** 4 (2001).
19. Li U.M., Lee B.S., Shih C.T., Lan W.H., Lin C.P., Cyclic Fatigue of Endodontic Nickel Titanium Rotary Instruments: Static and Dynamic Tests, J. Endod. **28**, 6 (2002).
20. M. Galal, T.M. Hamdy, Doc. Bull. Natl. Res. Cent. **44**, 121 (2020).
21. Li U.M., Lee B.S., Shih C.T., Lan W.H., Lin C.P., Cyclic Fatigue of Endodontic Nickel Titanium Rotary Instruments: Static and Dynamic Tests, J. Endod. **6** (2002).
22. S. Padavala, D. Ganapathy. Drug Invent. Today. **11,** 3 (2019).
23. T.M. Kumar, P. Vivekanandhan, M. Dhakshinamoorthy, R.M., Tamilselvi, A. Subbiya, Indian J. Public Health Res. Dev. **11,** 1 (2020).
24. S.A. Khasnis, P.P., Kar, A. Kamal, J.D., Patil J. Conserv. Dent. **21,** 2 (2018).