Original Article

Comparative evaluation of bending property and torsional resistance of three nickel-titanium files: A finite element analysis

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ABSTRACT

Aims: We aimed to investigate the effect of instrument length on the torsional resistance and bending property of three nickel–titanium files, namely ProTaper Gold (PTG), ProTaper Next (PTN), and HyFlex CM (HCM) using finite element analysis.

Materials and Methods: Three-dimensional models of each aforementioned system were created using the computer-assisted design (CAD) software SolidWorks® 2016 (Dassault Systèmes, SolidWorks Corp., Concord, MA, U. S.). Then, all models were imported to the ANSYS® Workbench 16 (Canonsburg, PA, U. S.) where the simulation was computed. The boundary conditions used to simulate the behavior of the endodontic instruments were in compliance with the ISO 3630 1 specification standards.

Results: It was observed that in bending test, HCM model exhibited load of 510.35 MPa with displacement of 6.05 mm, followed by PTG model (465.48 MPa) and 11.21 mm displacement, then PTN file model (440.74 MPa) and 10.30 mm displacement, whereas in torsional test the rigidity curve for HCM file (1.9673 N mm/Radian) lies much below PTG (6.4615 N mm/Radian) which clearly shows that HCM is flexible as compared to PTG and PTN.

Conclusion: Considering the high flexibility of the HCM file, it can be effectively used in severely curved root canals and PTG and PTN files in moderately curved root canals. It was also recommended that HCM files should not be kept in canals for a longer time because stresses might reach to ultimate level quickly which can cause fracture.

Keywords: Bending, finite element analysis, nickel–titanium files, torsion

INTRODUCTION

The primary goals behind root canal instrumentation are to eliminate micro-organisms with proper cleaning and shaping. Newer nickel–titanium (NiTi) rotary files with controlled memory and increased flexibility were introduced to improve root canal preparation of narrow and curved canals.[1]

However, in clinical practice, the fracture of the files is an event that should be considered to avoid performing the complicated technique of removing the separated instrument, subject to considerable risks, especially in the apical third. The prevalence of fracture in rotating NiTi instruments is in the range of 0.4%–5%.[2] Torsional stiffness and bending flexibility are the two most essential properties required in any rotary file, which determines file performance in clinical use. These two properties have been studied extensively and have been described as two of the most important causes of fracture.[3]

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Manufacturers have tried to improve the mechanical properties or fracture resistance of NiTi instruments by developing specific cross-sectional designs and producing different thermomechanically treated NiTi alloys.[2] ProTaper Gold (PTG, Dentsply Sirona) is designed similarly to ProTaper Universal (PTU) (Dentsply Sirona) but is manufactured using a gold wire (Dentsply Sirona). The gold heat treatment is a relatively advanced metallurgic process, which has two-stage transformation behavior and high austenite finish temperature.[3]

ProTaper Next (PTN; Dentsply Sirona, York, PA) is manufactured using M-wire and characterized by a unique movement known as "swaggering motion." These features make PTN more cyclic fatigue resistant than its previous version.[4] HyFlex CM (HCM; Coltene-Whaledent, Allstetten, Switzerland) rotary files are manufactured using a controlled memory wire (CM wire) that has been subjected to proprietary thermomechanical processing.[5]

A previous study[6] comparing PTG and PTN found that both the files produced less transportation and maintained more dentin than PTU file. PTN had less canal wall contact than PTG and PTU, but all file systems were able to instrument moderately curved mesial root canals of mandibular molars without clinically significant errors. Finite element analysis technique is used to determine stress and displacement of the structural object into finite number of elements by calculating the dynamic equilibrium among these elements and hence is one of the most standard, time-saving, economical, and successful engineering computational methods.[7]

There is paucity in evidences evaluating the torsional resistance and bending property of the aforementioned NiTi files using standardized numerical analysis. Therefore, we aimed to investigate the effect of instrument length on the torsional resistance and bending property of three NiTi files using finite element analysis.

MATERIALS AND METHODS

Endodontic instruments analyzed

After Institutional Ethics Committee approval (IRB/2019/VSPM00345), three commercially available NiTi rotary file systems, PTG (Dentsply Sirona, York, PA), PTN (Dentsply Sirona, York, PA), and HCM (Coltene-Whaledent, Allstetten, Switzerland), were selected for this study.

The cross-sectional designs of PTN, HCM, and PTG were rectangular, triangular, and convex triangular, respectively. The tip sizes of all files were PTG: finishing file F2 (0.40/0.6 v), HCM 25 (6%20), and PTN 2 size (25.06).

Creation of finite element model for nickel–titanium files

Real size simulated digital models of three NiTi instruments of size 25 and taper 0.06: PTG (Dentsply Sirona, York, PA), PTN (Dentsply Sirona, York, PA), and HCM (Coltene Whaledent, Allstetten, Switzerland) were obtained by computed tomography (CT) scanning. CT images were taken using multislice CT 64 machine (Model GE Discovery VCT, Germany) at 120 KV and 250 mA. With 0.4-mm slice thickness, the files were imaged using a stereomicroscope (6%/20, Carl Zeiss Jena) at X5, X10, and X16 magnifications to obtain a detailed shape.

To build the file's three-dimensional (3D) model, the file cross-section was drawn in two-dimensional (2D) using Computer aided design (CAD) software (Solidworks Software Package). The 2D file with (.prt) extension was converted into Stereolithographic (.stl) extension to be readable by programming software (MATLAB software).

Building of 3D model in the form of sections was performed by MATLAB software using the following data: taper of the file, change in pitch length, and cross-section changes [Figure 1]. After building of the 3D model on MATLAB, the files were imported to computer-aided design programs CAD (SolidWorks software package).

The file (.stl) extension was converted to.prt or. sldprt to be edited by computer-aided design programs CAD (SolidWorks software package). Finishing of the file 3D model was performed by building the tip and the handle of the file using computer-aided design programs CAD (SolidWorks software package). These steps were performed for each file [Figure 1a-c].

Finite element (FE) models of each file was constructed using Computed aided design (SolidWorks software package). The meshing of the models was done by Cosmos (SolidWorks software package) using linear, six-noded trihedral elements. The final FE model of the HCM instrument consisted of 2123 elements with 4025 nodes, the PTG consisted of 2695 elements with 5592 nodes, while the PTN consisted of 3132 elements with 5886 nodes [Figure 1a-c].

The boundary conditions used to simulate the behavior of the endodontic instruments were in accordance with ISO 3630 1 specifications. The simulated designs of the tested files were validated by two senior endodontists and examined graphically under their supervision with the aid of finite element method technical expert.

Bending resistance test

Cantilever bending was simulated by applying a concentrated load of 1 N and incremental displacement of 3 mm at the

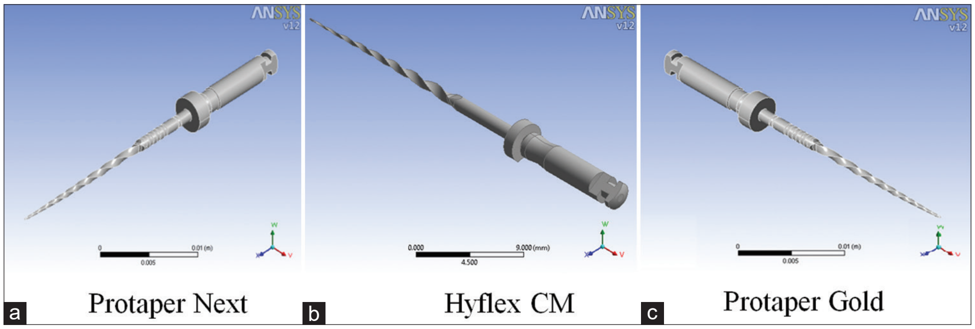

Figure 1: The boundary conditions used to simulate the behavior of the endodontic instruments aligned with the ISO 3630-1 specifications. (a) ProTaper next. (b) HyFlex CM. (c) ProTaper Gold

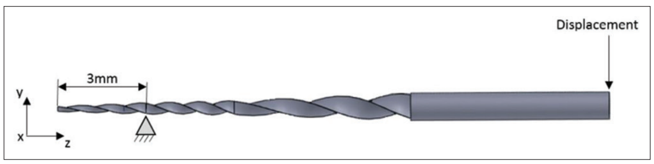

Figure 2: Graphical Representation of Bending resistance test Torsional resistance test

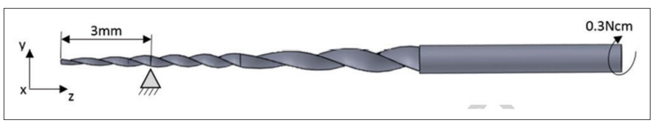

Figure 3: Graphical Representation of Torsional resistance test

tip of the file in 10 steps with its shaft rigidly held in place (Kim *et al*., 2009) [Figure 2]. The vertical displacement was measured, and the von Mises stress distribution was evaluated.

Torsional resistance test

A torsional force of 2.5 Ncm was applied to the shafts of the file models in a clockwise direction at 10° increment up to 360°.[8,9] while the last 4 mm of the tip was rigidly constrained. The von Mises stress distribution was evaluated [Figure 3].

Principal stresses upon loading were assessed and value was calculated according to 3D von Mises criterion as:

$$\sigma vM = (1/2[(\sigma 1-\sigma 2)\ 2 + (\sigma 2\text{-}\sigma 3)\ 2 + (\sigma 3-\sigma 1)\ 2])\ 1/2$$

The forces acting on the models by external structures like dentin were not taken into consideration. Color coding was given where red and blue colors denoted the high-stress and low-stress-bearing areas, respectively.

RESULTS

Static analysis

Load of 1 N applied at the tip with handle of file as fixed

When bending test was performed at the tip, the maximum stress value was related to HCM model 510.35 MPa with displacement 6.05 mm, followed by PTG model 465.48 MPa and 11.21 mm displacement and then PTN file model 440.74 MPa and 10.30 mm displacement [Figure 4].

Displacement of 2 mm applied at the tip with handle of file as fixed

When bending test was performed with displacement of 2 mm at the tip, the maximum stress value was observed in HCM model (524.53 MPa) with reaction of 0.0876 N at fixed support, followed by PTG mode 184.78 MPa and 0.178 N reaction and then PTN file model 167.74 MPa and 0.1436 N displacement [Figure 5].

Portion of 4 mm from the tip of file was kept fixed and torsion of 2.5 Nmm was applied at the handle

During torsion test, HCM model recorded 462.96 MPa von Mises stresses, which was more than that in PTG model 193 MPa followed by PTN model 176.15, indicating the higher flexibility of HCM file [Figure 4].

Incremental displacement of 2 mm was applied at the tip in 10 steps with handle of file as fixed

During torsion test, HCM model recorded 1400 MPa von Mises stresses at 20 mm displacement at the tip and deformed at 2.78 mm which was more than that in PTG model 575.33 MPa followed by PTN model (534.28), indicating that HCM file reaches to higher stress swiftly with 3 mm displacement beyond which it can gets fractured [Figure 6].

Portion of 4 mm from the tip of file was kept fixed and handle is rotated by 360° with the increment of 10°

During torsion test, PTG model recorded the highest 1367.7 MPa von Mises stresses when rotated at 360° when portion of 4 mm from the tip was kept fixed followed by PTN model at 1311.9 MPa followed by HCM, i.e., 982.38 MPa, indicating that the magnitude of von Mises stresses observed in PTG is more when handle is rotated by 360 thereby. Furthermore, it could be observed in the rigidity curve [Figure 7] for HCM file (1.9673 N-mm/Radian) lies much below PTG (6.4615 N-mm/Radian) which clearly shows that HCM is flexible as compared to PTG and PTN.

It was also seen that HCM requires more rotations as compared to PTG and PTN file models to transform in different material phases. This indicates that HCM has good shelf life when subjected to torsional loads [Table 1].

DISCUSSION

This study compared the mechanical properties of three NiTi files, namely HCM, PTG, and PTN. These NiTi instruments share the same manufacturing technique by using M-wire technology. A rectangular cross-section design and the asymmetric rotary motion were observed for the PTN, modified convex triangular cross-section at the tip end, and a convex triangular cross-section at the coronal end for the PTG and double-fluted Hedström design with positive rake angle design for HCM.

Finite element analysis or any other mathematical simulation analysis may show a difference from the clinical situation. Some conditions were not taken into consideration, such as eventually gradients of temperature, dentin wall friction with the instrument used, and complicated root canal anatomy. On the other hand, the applied loads and boundary conditions for both tested file models might give reliable indication about their expected clinical performance.[7]

The amount of torsional stresses accumulated in the tested NiTi files depends on their cross-sectional design, chemical composition of alloy, and thermomechanical technology applied during manufacturing.[8,9] The size of the instrument in the canal also has a significant influence on the amount of torsional load on the file.[10]

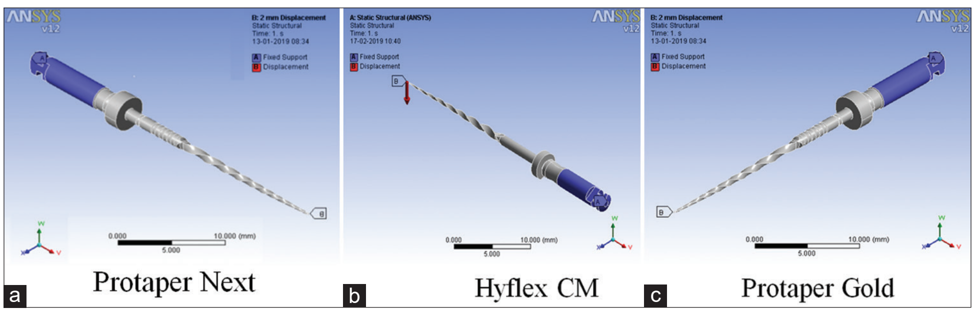

Figure 4: Static analysis when load of 1 N applied at the tip with handle of file as fixed. (a) ProTaper next. (b) HyFlex CM. (c) ProTaper Gold

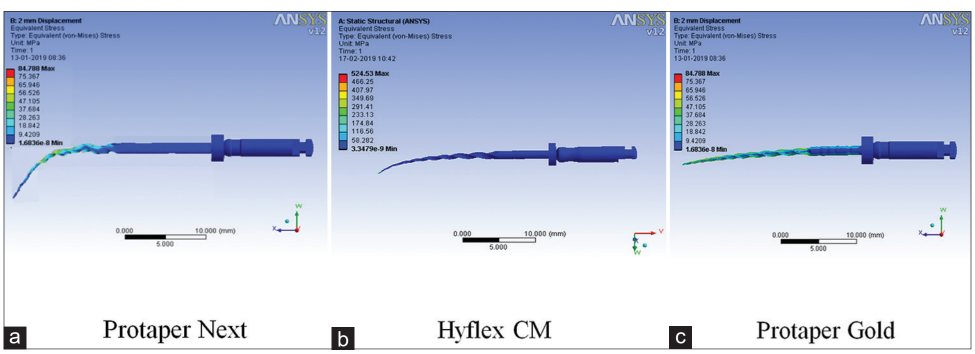

Figure 5: Static analysis when the displacement of 2 mm applied at the tip with handle of file as fixed. (a) ProTaper next. (b) HyFlex CM. (c) ProTaper Gold

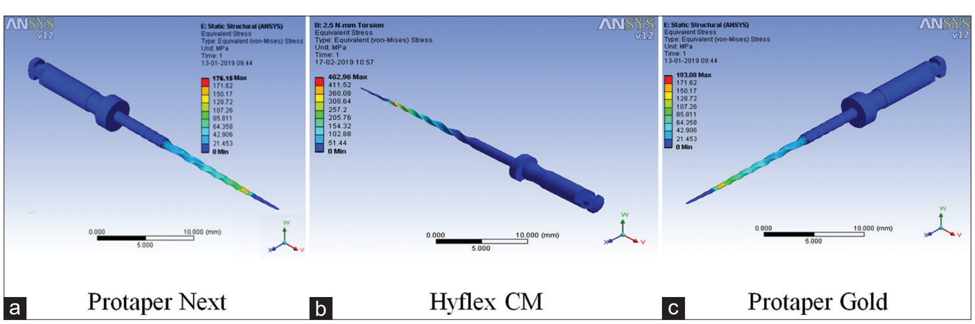

Figure 6: Static analysis when portion of 4 mm from the tip of file was kept fixed and torsion of 2.5 N/mm was applied at the handle (blue color denotes low-stress area, whereas red indicates high-stress area). (a) ProTaper next. (b) HyFlex CM. (c) ProTaper Gold

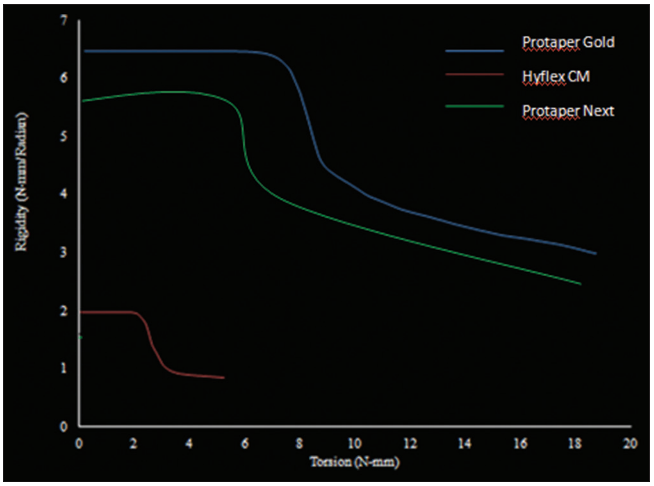

Figure 7: Rigidity curve of the endodontic files

Table 1: Different material phases of the endodontic files

File	Austenitic phase (0-500 MPa)	Transition phase (500-540 MPa)	Martensitic phase (540-1400 MPa)
HyFlex CM	110.72°	141.68°	Above 141.68°
ProTaper Gold	66.44°	99.74°	Above 99.74°
ProTaper Next	62.35	94.48	Above 94.48

CM: Controlled Memory

In this study to simulate the repetitive locking of NiTi files during canal preparation, a shear moment (torsion) 2.5 N/mm moment of force was applied to the shaft of the tested files in a clockwise direction, while the last 4 mm of the tip was rigidly constrained using the FE analysis.

As mentioned before, the file cross-section is a major parameter that affects the instrument lifespan, as the shape of the cross-section and the angles that contact dentinal walls while cutting directly affect the cutting efficiency of instrument.[10]

The HCM cross-sectional design allows more stress accumulation in the file model of maximum von Mises stress during torsion testing of value 753.7 MPa, while the larger rectangular cross-section of PTN showed 608 MPa von Mises stress during torsion testing.

Kim *et al*. reported that under torsional stresses, the NiTi files were affected by many factors, such as the shape and geometry of the cross-section, radial land, and area of the continuous inner core.[9]

The combination of these factors on the distribution of stresses along the length of the endodontic files under torsion remains undetermined. The present study showed that the effect of the alloy is less important than the cross-section geometry. There are numerous studies relating cross-section diameter to the torsional resistance.[11,12]

The degree of flexibility of NiTi rotary instruments is a crucial property in predicting the mechanical behavior and performance of endodontic instruments during the preparation of curved canals.[13]

In the current study, the two instrument models were fixed 4 mm away from the tip because this represents the maximum tension for instruments yielding to bending, as the maximum curvature is found in the majority of root canals corresponding to that point. The PTN showed higher bending 923 MPa and displacement of the file model with 11 mm in comparison to the HCM 583.1 MPa and 4.5 mm, respectively.

The HCM file has a decreasing taper while the PTN has a progressive taper at the apical section while a decreasing taper at the coronal section, which makes the PTN model more flexible than the HyFlex model at the apical part. This findings supports the notion that wire containing martensite displays flexible and ductile properties owing to its microstructural characteristics.

The higher taper of HCM (8%) at the tip makes it more rigid thereby exhibits less bending characteristics and subsequently causes less file displacement, while the PTN file has a 6% taper with asymmetric rotary motion, which renders the file more flexible for bending and thus results in more displacement.[5,6] This supports the results conducted from the present study. This comes in agreement with Shen *et al*.[14]

The present study being *in vitro* in nature, could not be extrapolated with the dynamics of oral conditions in vivo, therefore, future clinical trials should be conducted so as to have an insight on their *in vivo* nature. Furthermore, long-term studies were needed in order to evaluate the efficacy of these NiTi files over a long term. However, the present findings could explore new dimensions in the mechanical behavior of these files which may benefit the clinicians to use them in appropriate situations.

CONCLUSION

Within the limitations of the study, it was observed that HCM file is more flexible as far as tip portion is considered compared to PTG and PTN. Considering the high flexibility of HCM file, it can be effectively used in severely curved root canals and PTG and PTN files in moderately curved root canals. Furthermore, HCM has good shelf life when subjected to torsional loads, and at the same time, HCM file will fracture early in higher bending loads when compared PTG and PTN files.

Considering all these factors, HCM files should not be kept in canals for a longer time because stresses might reach to ultimate level quickly which can cause fracture.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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