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ORIGINAL ARTICLE

Comparative Evaluation of Stress Distribution Against the Root Canal Wall at Three Different Levels by Using TruNatomy, XP-endo Shaper, F360, and 2Shape Files–A Finite Element Analysis

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ABSTRACT

Objective: The aim of this *in vitro* study was to assess the stress distribution of novel endodontic rotary files of different cross sections and metallurgy against the root canal wall at three different levels by using finite element analysis.

Methods: A total of 60 novel NiTi rotary files were included in this study after being scanned for any surface deformities using a scanning electron microscope. The scanned files were assigned into 4 groups of 15 samples each based on their metallurgy and design: Group A-TruNatomy, Group B-XP-endo Shaper, Group C-F360, and Group D-2shape files. ANSYS® 15 Workbench finite element software (Canonsburg, Pennsylvania, United States) was used to numerically analyse the stress created by computer-aided models of these instruments on the dentinal wall of a simulated root canal to test the mechanical behaviour of these files. All data were analysed using one-way ANOVA with post hoc Tukey analysis, the Shapiro Wilk test, and Levene's test. The significance level was set at 5%.

Results: XP-endo Shaper files employed minimal stress on the surface of dentine during instrumentation, and F360 files exerted maximum stress on the dentinal wall. However, no statistically significant difference was found among the groups in relation to the amount of stress produced at the distinct levels of the root canal wall ($p>0.05$).

Conclusion: There was no discernible difference in stress generation among the four groups in the current investigation. Therefore, it can be inferred that the upgrade in design and metallurgy of rotary files has the potential to downgrade the stress during the shaping of the canal and the menace of instrument breakage during their clinical usage.

Keywords: Computer-aided design, finite element analysis, nickel- titanium, rotary files, TruNatomy, XP-endoShaper

HIGHLIGHTS

- This study investigated the mechanical behaviour of novel NiTi rotary files having different cross sections and metallurgy inside a simulated curved root canal system.
- The files manufactured from conventional super-elastic NiTi alloy produce more stress than thermo-mechanically heat-treated files.
- The files, having a smaller cross-section and a smaller core area, distributed the least amount of stress on the dentinal wall.
- A progressive increase in the pitch of an endodontic file can reduce the stress generated on them by preventing their screwing in during instrumentation inside the root canal.

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INTRODUCTION

During the endodontic procedure, mechanical preparation of the root system aids in optimising the shape of the root canal for optimal root canal filling. Therefore, for the success of an root canal treatment procedure, suitable instruments and their precise application through biological and mechanical preparation are of the utmost importance (1).

Presently, the files fabricated with NiTi alloy have become popular for the mechanical preparation of a root canal because of their inherent properties of superelasticity and shape memory, which impart additional elastic flexibility and resistance to torsional fracture to them. Despite the advent of NiTi files with superior qualities, there is still a risk of unpredictable instrument fracture during the preparation of root canals, especially in severely curved canals (2, 3).

Instrument separation is one of the most common causes of treatment failure during the endodontic management of teeth. According to the American Association of Endodontics, the reported frequency rate for fractured rotary instruments lies in a range of 0.4% to 5% of cases (4).

Clinical and metallographic forms can be used to categorise the causes of instrument separation. The clinical cause of separation includes the failure to remove coronal and cervical interference, and the metallographic causes are due to the insufficient kinetics of NiTi instruments, which results in the instruments seperation either due to cyclical flexural fatigue, torsional failure, or a combination of both (5).

When an instrument is freely rotated inside a curved root canal, a continuous cycle of tension and compression at the instrument's greatest flexure point causes cyclical flexural fatigue. The rationale behind this could be due to excessive usage of metal alloys or other variables such as corrosion and changes brought on by thermal expansion and contraction (6). Torsional fracture occurs when the elastic limit is surpassed, primarily because the instrument's tip becomes locked in the canal wall and the shank rotates continuously (7).

Cheung et al. (8) stated that 93% of the separation of endodontic files occurs due to flexural fatigue. Galal and Hamdy (9) reported that additional factors, such as raw materials, design, and manufacturing techniques, had a substantial impact on the separation of instruments.

The geometry of the endodontic instrument, such as its cross section and taper, as well as the geometry of curved canals, such as the radius length, arc length, and position of the arc, determine the magnitude of tensile stress and compressive stress acting on the instrument (10). So, manufacturers continuously develop new instruments with enhanced metallurgy and designs to meet the need for endodontic tools with improved mechanical qualities that will function more effectively and safely.

The recently introduced F360 file system (Komet, Brasseler GmbH & Co., Lemgo, Germany) is created from traditional, superelastic NiTi alloy. This system requires only two files to clean and shape the root canal system. It has a narrow core and a double-S-shaped thin cross- section, which enables high cutting efficiency, flexibility, and minimization of canal transportation (11).

A contemporary file system called XP-endo Shaper (FkG Dentaire SA, La Chaux-de-Fonds, Switzerland), which features a snake-like design and exclusive max wire technology, has an initial taper of 0.01 in its M phase while it is cool. According to the molecular memory of the austenitic phase, the taper changes to 0.04 when exposed to body temperature (35°C). Due to their special qualities, these files are easily adaptable to canal imperfections, have exceptional resistance to cyclic fatigue, and reduce the possibility of dentine microcracks (12).

TruNatomy (TN; Dentsply Sirona, Maillefer, Ballaigues, Switzerland) is a file system made of 0.8 mm NiTi wire rather than the 1.2 mm NiTi wire used to make most generic files; they have an off-centred parallelogram cross-sectional design. It consists of four shaping files: prime (.04), small (.04), and medium (.03) in size. Due to its enhanced flexibility and cyclic fatigue tolerance, TruNatomy has a lower chance of separation (13, 14).

The 2Shape file system (Micro Mega, Besancon, France) comprises two files, TS1 (25/.04) and TS2 (25/.06). They are fabricated from T-Wire technology after grinding a NiTi alloy with a cross-section of a triple helix along with two main cutting edges for cutting efficiency and one secondary edge for increased debris removal (15). One study showed that these files are more flexible, resistant to cycle fatigue, and have a low elastic modulus when compared to traditional instruments (16).

Finite element analysis (FEA) is a method generally used for a thorough analysis of the stress distribution of endodontic rotary files against the root canal wall. In this procedure, the complex structure of a rotary file is divided into multiple small, simple-shaped elements so that each deformation (strain and stress) may be calculated more readily than for the entire, undivided large structure. However, this method requires a large amount of data input and a longer execution time (17).

With emerging technology, there is a plethora of different endodontic file systems made available by manufacturers with improved mechanical properties. However, they still have a risk of fracture. Till now, more evidence is needed to evaluate the importance of design and metallurgy in novel NiTi rotary instruments, and how they contribute to the development of stress on the instrument when exposed to rotational-bending force during instrumentation.

Therefore, the aim of this *in vitro* study was to assess the stress distribution of novel endodontic rotary files of different cross sections and metallurgy against the root canal wall at three different levels by using finite element analysis. The null hypothesis of the study postulated that there was no appreciable variation in the distribution of stress among any group.

MATERIALS AND METHODS

The university ethics committee reviewed and approved the present research under the code BBDCODS/03/2020/No. 31. The study was conducted in accordance with the Declaration of Helsinki.

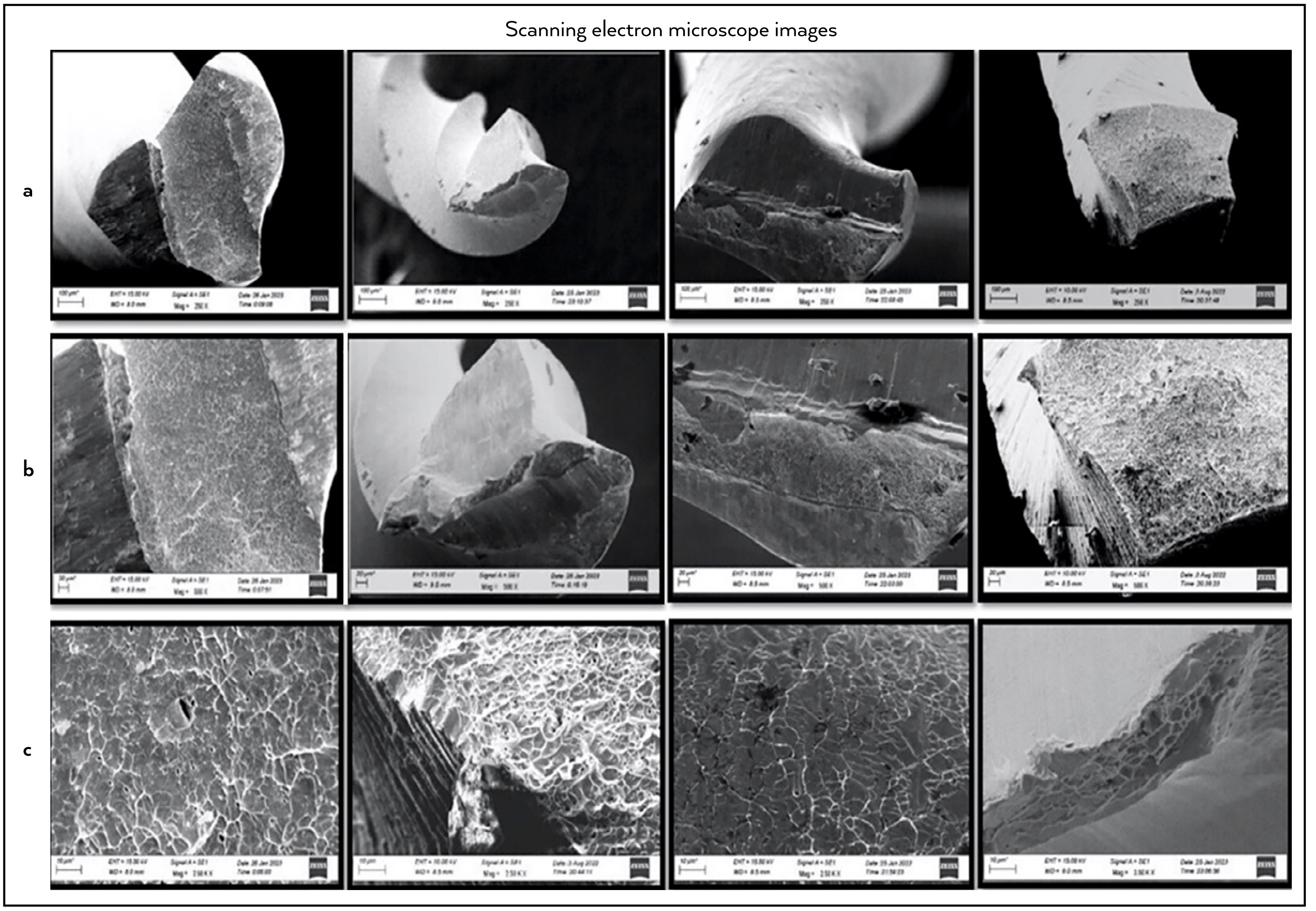

Figure 1. (a) Scanning electron microscope images (CARL ZEISS Microscopy Ltd EVO-SEM MA15/18) of all four groups of novel endodontic rotary files at a magnification of 250X (b) 500X and (c) 2500 X to check the surface irregularities and microcrack formation

The G Power software (version 3.0) was used to estimate the sample size. The effect size was 0.50 using an alpha level of 0.05 and a power of 95%; the estimated minimum sample size (n) was 60 samples. Rotary files were selected based on their cross section and metallurgy with a fixed taper of 4% to create four different groups (n=15).

Files were cleaned with 70% w/v ethanol before starting the sample preparation to ensure no external polish or coating was present on the surface and to make the surface free from contamination. After cleaning the files with ethanol, the working surface was marked in three equal parts with the help of a marking pen as per the geometry. Scanning Electron Microscope (Carl Zeiss Microscopy Ltd. EVO-SEM MA15/18, GmbH, Oberkochen, Germany) investigations of files were done in both scattered electrons (SEs) and backscattered electrons (BSEs) modes at a magnification of 250x, 500x, and 2500x under high resolution (Fig. 1). Likewise, corresponding sample areas were exposed to energy-dispersive X-ray spectroscopy (EDS) analysis for elemental characterizations and to check for surface irregularities and the presence of microcracks. The real-size images of these novel NiTi files were obtained in three dimensions, and after that, the files were scanned using Exocad software (Exocad GmbH, Align Technology, Inc. company, Darmstadt, Hessen, Germany).

Later, a geometrical model, i.e., a 3D computer aided design (CAD) model of rotary files, was designed. The obtained files in stereolithography (STL) format were converted into initial graphics exchange specification (IgES) format by Solidworks version 2013 software and further processed by Analysis System (ANSYS) Workbench 15.0 (Canonsburg, Pennsylvania, United States) to reproduce a 3D model of each instrument for further analysis.

Preparation of 3D Finite Element Models

The 3D finite model of the simulated root canal was constructed with a 16 mm, 45-degree root curvature, a 6 mm radius, and an apical diameter of 0.5 mm of the apical foramen. NiTi rotary files were created using ANSYS Workbench 15.0 software. All simulated rotary files had a standard length of 25 mm, a working surface of 16 mm with a taper of 0.04 (Fig. 2).

After designing the virtual root canal and the rotary files, all the observations were done on a structural analysis module of ANSYS for retrieving equivalent Von Mises stress in later steps. The mesh generation was performed using Solidworks version 2013 software (Dassault Systèmes SOLIDWORKS Corp., Waltham, Massachusetts, United states) in ANSYS Workbench 15.0. Consequently, 3D finite models were divided into 3D brick elements and nodes (Fig. 3).

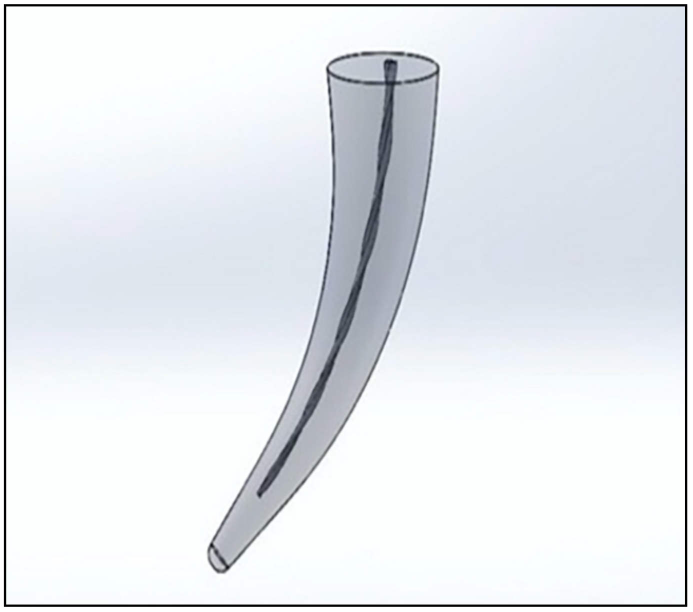

Figure 2. Computer aided design (CAD) model of novel endodontic rotary file and simulated root canal

For a 3D finite model of a root canal, the number of nodes and elements is as follows: nodes were 40751 and elements were 24660. Similarly, the 3D finite models of all tested rotary files were divided into nodes and elements.

The characteristic material properties of each type of NiTi were assigned as per the literature (18–21) in the engineering data feature of ANSYS software. After assigning the data for geometry and material properties, the data was transferred to a mechanical modular for analysis for the application of load and boundary conditions.

Loading and Boundary Conditions

After inserting the files inside the simulated root canal, the virtual rotations of 180 degrees were performed three times at a rate of 300 rpm with 1.5 Nm torque in a root canal with a 45-degree curvature. After this, the displacement of nodes was calculated, and the stress was calculated at a point where maximum stress generation was seen (Fig. 4). Later, all the samples were analysed one by one based on their cross-sections and material properties.

Afterwards, for calculating and evaluating the stress generated on the instrument, the Von Mises stress formula was used. and the means obtained were tabulated for statistical analysis.

Statistical Analysis

All the obtained values were statistically analysed using IBM SPSS statistical programme version 23.0 (IBM Corporation, Armonk, New York). The mean and standard deviation were provided in the descriptive statistics, and the level of significance was set at 5%. The intergroup comparison of the difference in mean scores was done using one-way ANOVA followed by post-hoc Tukey analyses. The Shapiro-Wilk test and the Levene test were used to analyse the data distribution and variable homogeneity, respectively.

RESULTS

The data of all four groups—Group A-TruNatomy, Group B-XP-endo Shaper, Group C-F360, and Group D-2Shape—were found to be homogenous and normally distributed. For each variable, the mean and standard deviation (SD) were determined.

Von Mises Stress Analysis

The XP-endo Shaper model exhibited minimum stress in all three areas of the simulated root canal, followed by the 2Shape model. However, in the coronal area of the simulated root canal, the TruNatomy model (453.59 MPa) demonstrated less stress on dentinal walls than the 2Shape model (456.59 MPa). The F360 model exerted the maximum stress on the dentinal wall among all the tested files. The stress analysis for all the groups at the apical, middle, and coronal levels is provided in Table 1.

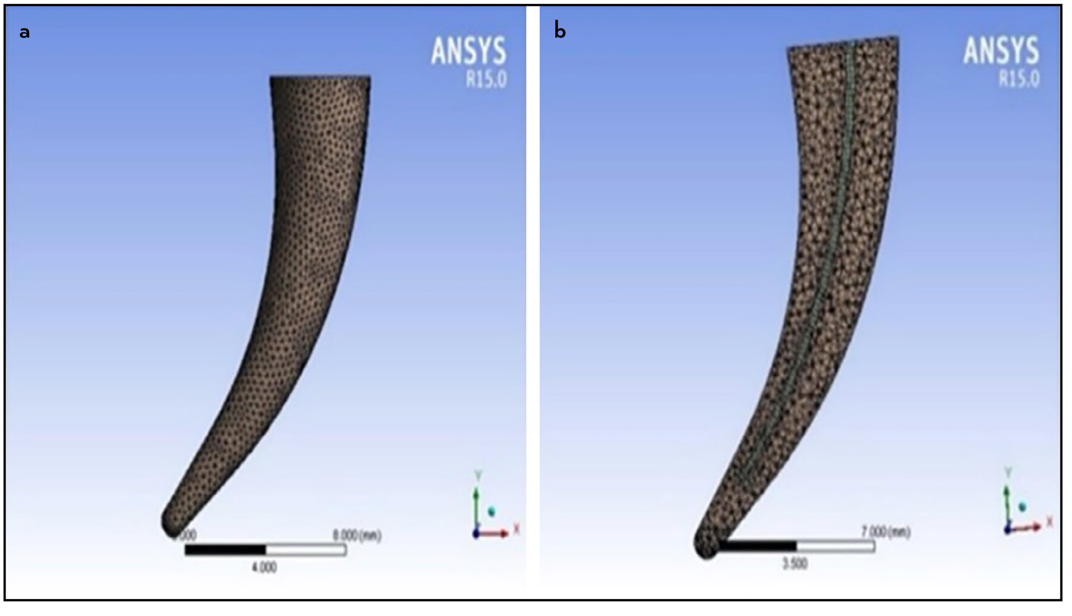

Figure 3. Mesh of the prepared CAD model of (a) simulated root canal and (b) novel endodontic rotary file was laid down followed by determination of nodes and elements

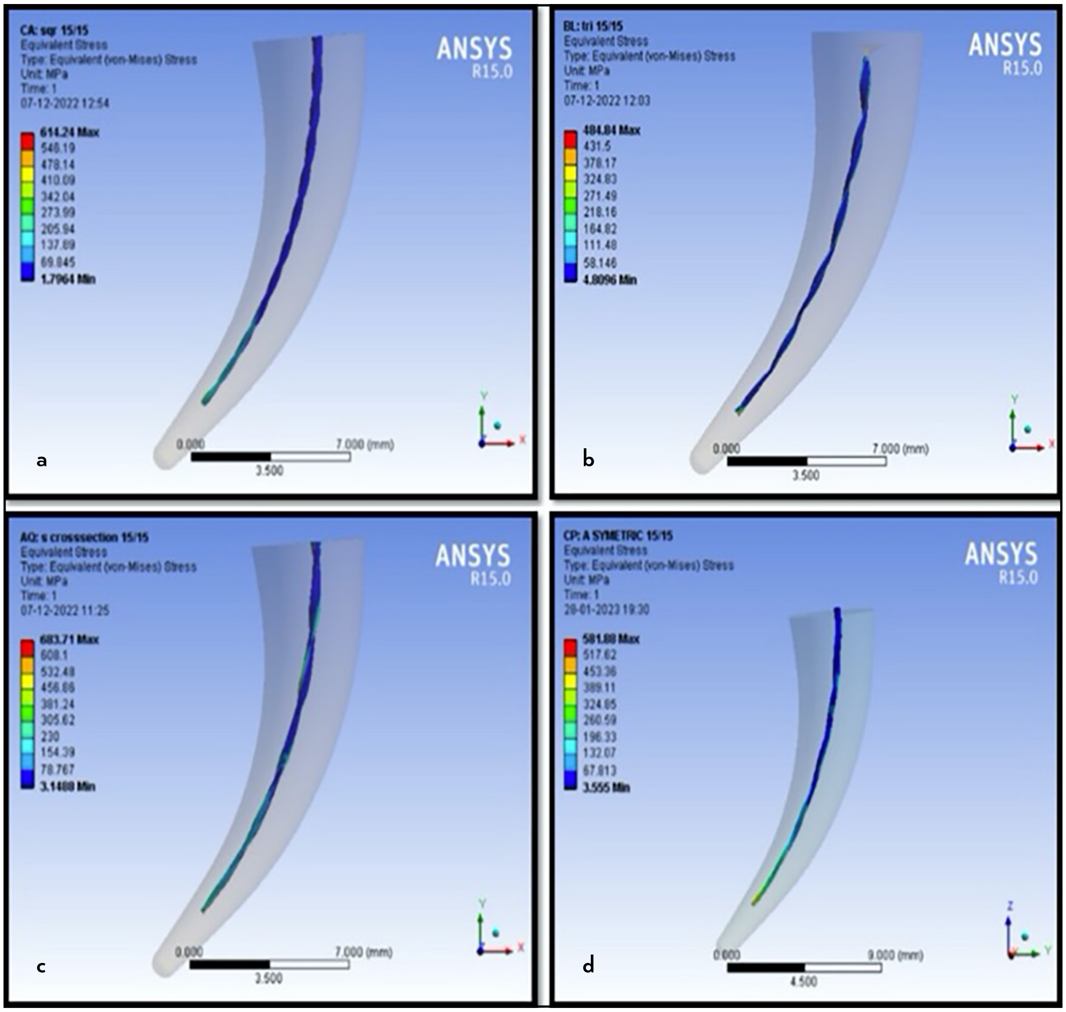

Figure 4. In the finite element analysis (FEA) findings of (a) the TruNatomy file, (b) the XP-endo Shaper file, (c) the F360 file, and (d) 2Shape file, warmer hues denote areas of high mechanical stress because they show the severity of the mechanical stress. Areas with cooler colours are less stressful. All the models showed similar stress distribution at the apical and middle areas, i.e., from the coronal level to the apical level, stress values are rising. except the TruNatomy model. The TruNatomy model showed a lesser distribution of stress towards the coronal area compared to the 2Shape and F360 models. The stress was found to be distributed more towards the apical portion of the instrument and root canal and less towards the coronal

According to the tests, there were no statistically significant differences in the parameters between all four groups (Fig. 5).

DISCUSSION

The finite element method (FEM) applied in this study is a beneficial approach for evaluating the mechanical behaviour and stress distribution of endodontic rotary instruments subjected to a controlled simulated condition through mathematical analysis, permitting assessment of each geometrical design parameter distinctly (9).

In this study, a simulated root canal was used, which was in accordance with the study carried out by Basheer et al. (21) and Kim et al. (22). This method does not rely on an externally applied force, as was the case in earlier studies for producing stress, and it relates both bending and torsion to create a combined loading and to provide a fixed deflection at 45 degrees (23). However, the inability to assess the dragging force brought on by the cutting edge's contact with the dentine was one of the drawbacks of the boundary conditions described by Kim et al. (22). The finite element analysis technique is very helpful for observing stress behaviours that are difficult to measure through physical examinations. A few studies have examined the number of cycles to fracture using the FEA approach (24, 25). Recent criticism of the proposed ISO standard experimental fatigue test has focused on the fact that it is essentially stationary fatigue. The FEA method is more appropriate since it might avoid the customary costly trial-and-error strategy based on repetitive prototype manufacturing and testing.

In the present study, XP-endo Shaper files generated a stress of 454.02 MPa (Table 2) on the dentinal wall, which was the least amongst all the tested files at a distinct level of the apical, middle, and coronal thirds of the simulated root canal (Tables 3-5). The least amount of stress in these files can be attributed to their unique small triangular cross-sectional design and a thin metallic adaptive core. Kim et al. (26) stated that the reason for the reduced value of Von Misses stress is due to a

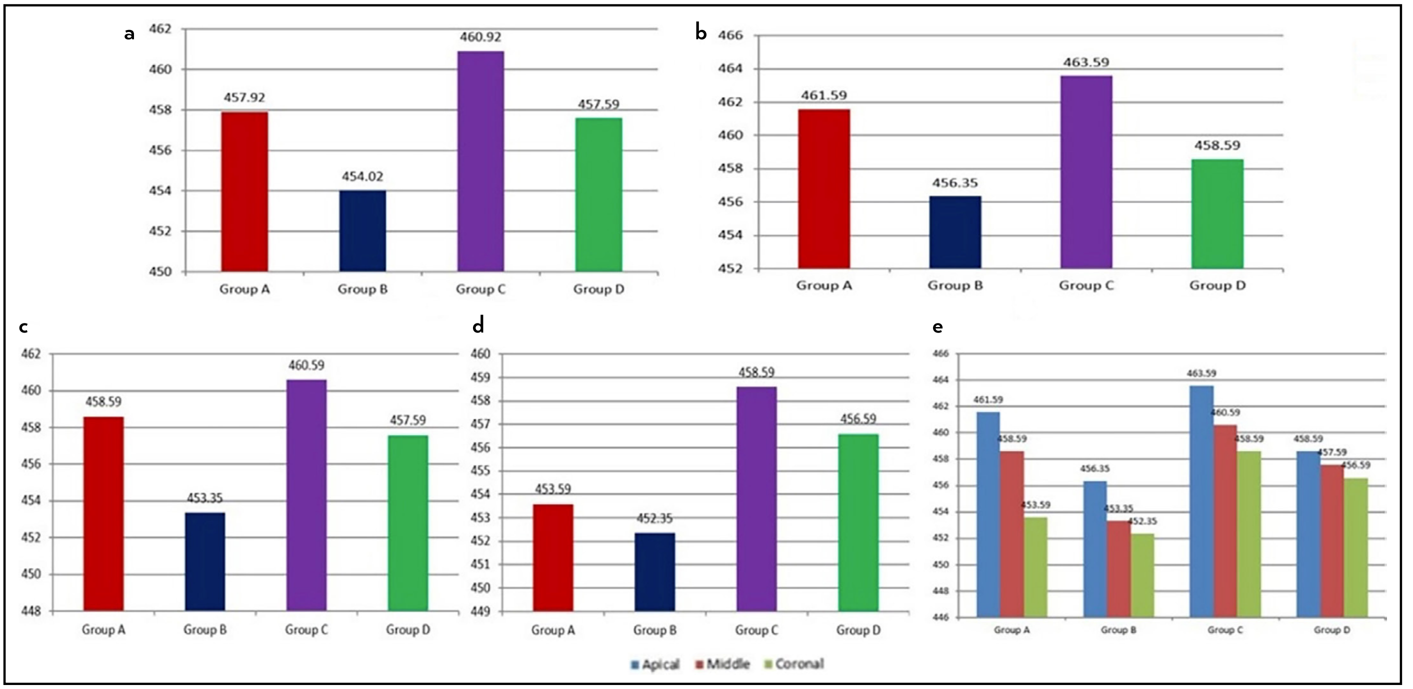

Figure 5. Comparison of mean (Standard deviation) values of all four novel endodontic rotary files (a) average stress generated by group A, B, C and D (P value of more than 0.05 is non-significant when analysed using one way ANOVA), (b) stress generated by group A, B, C and D (P value of more than 0.05 is non-significant when analysed using one way ANOVA) at apical one-third, (c) stress generated by group A, B, C and D (P value of more than 0.05 is non-significant when analysed using one way ANOVA) at middle one-third, (d) stress generated by group A, B, C and D (P value of more than 0.05 is non-significant when analysed using one way ANOVA) at coronal one-third , and (e) the mean stress produced by all four groups at the apical, middle, and coronal thirds of the root canal was compared within each group and the difference was statistically non-significant between the apical, middle, and coronal thirds

ANOVA: Analysis of variance

decrease in the cross-sectional perimeter and surface area of the rotary file. Studies have reported that instruments with a smaller central core area exert less stress on the dentinal wall (27, 28). Therefore, due to their unique design, these files have a nominal connection—one point of contact with the dentinal wall of a root canal. To substantiate this reason, Oh et al. (20) reported that the contact time between the XP-endo Shaper and root canal is less during rotation, and this could have resulted in lower stress during bending. Galal et al. (10) found that stress accumulation is directly related to the cross-sectional area of the rotary file. In addition, the booster tip of the file with six cutting edges might have turned out to generate minimal stress during the apical progress of the file inside the root canal, i.e., 456.35 MPa (Table 1).

The 2Shape files yielded a moderate stress of 458.59 MPa (Table 1) on the modelled dentinal wall, which can be attributed to its triple helix cross section, which could have resulted in reduced contact with the root canal, leading to lower stress on walls (29). This outcome of the study is in accordance with the study of Medha et al. (17) who assessed the distribution of forces in the apical third of the curved root canal and found that this type

TABLE 1. Stress comparison between different novel rotary files at apical, middle, and coronal one- third

Tested files	Apical one third (MPa)	Middle one-third (MPa)	Coronal one third (MPa)	p
TruNatomy	461.59	458.59	453.59	0.715
XP-endo Shaper	456.35	453.35	452.35	0.912
F360	463.59	460.59	458.59	0.769
2Shape	458.59	457.59	456.59	0.923

TABLE 2. Intergroup comparison of novel endodontic rotary files

Tested files	Mean (MPa)	Standard deviation	Standard error	p
TruNatomy	457.92	1.8	0.47	0.498
XP-endo Shaper	454.02	0.86	0.23	0.498
F360	460.92	1.83	0.48	0.498
2Shape	457.59	1.84	0.47	0.498

TABLE 3. Stress comparison between different novel rotary files at apical one- third

Tested files	Mean (MPa)	Standard deviation	Standard error	Minimum stress	Maximum stress	p
TruNatomy	461.59	1.78	0.466	458.04	465.19	0.764
XP- endo Shaper	456.35	0.88	0.221	454.81	457.84	0.764
F360	463.59	1.81	0.459	460.04	467.19	0.764
2Shape	458.59	1.84	0.483	455.04	462.19	0.764

TABLE 4. Stress comparison between different novel rotary files at middle one- third

Tested files	Mean (MPa)	Standard deviation	Standard error	Minimum stress	Maximum stress	p
TruNatomy	458.59	1.81	0.467	455.04	462.19	0.769
XP-endo Shaper	453.35	0.87	0.224	451.81	454.84	0.769
F360	460.59	1.82	0.468	457.04	464.19	0.769
2Shape	457.59	1.84	0.469	452.04	459.19	0.769

TABLE 5. Stress comparison between different novel rotary files at coronal one- third

Tested files	Mean (MPa)	Standard deviation	Standard error	Minimum stress	Maximum stress	p
TruNatomy	453.59	1.84	0.463	450.04	457.19	0.569
XP-endo Shaper	452.35	0.85	0.222	449.81	452.84	0.569
F360	458.59	1.87	0.466	455.04	462.19	0.569
2Shape	456.59	1.81	0.458	453.04	460.19	0.569

of cross-section resulted in reduced internal residual stress. According to Diemer et al. (29), a triple helix cross-section tends to produce a smaller amount of axial stress. In addition, these files exhibit deeper flutes in the triple helix, which results in a smaller core diameter. This could have caused the stress to spread to a smaller area. This finding is in agreement with Gharechahi et al. (30) who evaluated the stress distribution of files in different types of canal anatomies, and found that the files having a triple helix design produced less stress and a better stress distribution. In contrast to the results of this study, Fornari et al. (31) reported that this type of design causes an increase in friction and loading while shaping the root canal. Similarly, Turpin et al. (32) found that a triple helix design would elevate the stress during bending in curved canals. Procedural variations and different experimental conditions might have caused discrepancies in the outcome of the present study with these studies.

The 2Shape file has a progressive increasing pitch design, which could have resulted in a decreased level of stress by avoiding the screw in force. Ha et al. (33) mentioned in their study that the torsional stress increases when the screw-in of the file occurs inside the root canal. Another study by Ha et al. (34) stated that the screw-in force decreases with decreasing pitch. Similarly, Diemer et al. (35) affirmed in their study that an increase in pitch can reduce torsional stress by decreasing the screw-in effect.

In this study, TruNatomy files generated a stress of 461.59 MPa (Table 1). The rationale for the resultant stress is very likely to be because of its exclusive, distinctive design of a core diameter of 0.8 mm NiTi wire as a replacement for 1.2 mm NiTi wire and due to its off-centred cross-sectional design that produces a snake-like motion inside the canal that reduces the stress upon rotational motion (14). Conversely, Galal and Hamdy (9) found that the eccentric cross-section of files resulted in more stress generation.

The stress exerted by TruNatomy files was found to be less towards the coronal area i.e., 453.59 MPa (Table 5) when compared to 2shape files, and the reason for this can be attributed to the regressive taper of TruNatomy files. However, in the apical region, the stress distribution by the TruNatomy files was significantly higher than that by the 2shape files. This could be due to the inappreciably larger tip diameter of TruNatomy files (0.26) in relation to that of 2Shape files (0.25). Another study related the number of cycles in the fatigue test with the numerical stress, and found that the number of cycles to fracture increased when maximum stress was reduced (36). Few studies reported that the TruNatomy files have a reduced number of cycles to failure than the 2Shape files; this could be the reason for their resultant value of stress generation (37, 38).

The F360 rotary files examined in this study produced the maximum amount of stress (460.92 MPa) amongst all the other tested groups (Table 2). The reason could be due to their manufacturing process, as they are developed from conventional superelastic NiTi alloy. Because of this, they can remain in the austenite phase while being used in a clinical setting, which could have caused uneven stress distribution while recovering their form after instrumentation (39, 40). The results of this investigation are congruent with those of Ba-Hattab et al. (41), who examined the shaping ability of the F360 file with a NiTi rotary file system manufactured from different NiTi wire and found that the F360 file created an uneven distribution of stress on the root canal walls. In addition, F360 files had an S-shaped cross-section, which might have exerted more stress on the dentinal wall. Prados-Privado et al. (42) compared the bending and torsion responses of WaveOne, WaveOne Gold, Reciproc, and Reciproc Blue. They observed that an S-shaped cross-section file (The Reciproc file) generated more stress, which is in accordance with our results.

After the statistical evaluation, it was found that the amount of stress generated by all four tested novel NiTi files was not significant. The stress was found to be least at the coronal part of the root canal, followed by the middle part, and the stress was found to be maximum at the apical area. The explanation for the rise in stress from the middle to the apical area after the virtual instrumentation in this investigation may be related to a reduction in the radius of curvature of the root canal model (43, 44).

Designing a finite element model is difficult, complicated, expensive, and time-consuming because it necessitates a thorough understanding of computer-aided design (CAD) to accurately mimic the geometric depiction of an endodontic rotary file parameters which also requires additional knowledge to simulate the mechanical behaviour and stress dispersion of rotary files against the dentinal wall.

Since there is no single endodontic instrument system that is appropriate for every clinical condition, more research is necessary to confirm the model used in this study. It is important to understand how the structural features may affect the amount of stress placed on the endodontic instrument to prevent fracture in actual use.

CONCLUSION

Within the parameters of this study, the XP-endo Shaper files distributed the least amount of stress against the simulated root canal wall. According to the results of this research, alterations in the design of a file (cross section, core area) and a post-machining thermomechanical heat treatment of endodontic files could be more efficient methods of lowering the likelihood of instrument breakage owing to stress distributed during the shaping of curved root canals.

Disclosures

Ethics Committee Approval: The study was approved by the Babu Banarasi Das College Of Dental Sciences Ethics Committee (no: BBDCODS/03/2020/31, date: 07/04/2022).

Authorship Contributions: Concept – R.S., S.D., P.S., P.S.S., R.G.; Design – R.S., S.D., P.S.S.; Supervision – R.S., S.D., P.S., P.S.S.; Funding – R.S., R.G.; Data collection and/or processing – R.S., R.G.; Data analysis and/or interpretation – R.S., S.D., P.S., P.S.S.; Literature search – R.S., S.D., P.S.; Writing – R.S., S.D., P.S.; Critical review – R.S., S.D., P.S., P.S.S., R.G.

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