Journal of Oral Biology and Craniofacial Research 14 (2024) 692–699

Contents lists available at ScienceDirect

Journal of Oral Biology and Craniofacial Research

journal homepage: www.elsevier.com/locate/jobcr

Comparative evaluation of pediatric endodontic rotary file systems to bending and torsion tests: A finite element analysis

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A R T I C L E I N F O

Keywords:
Finite element analysis
Pediatric rotary files
Material testing
Stress

A B S T R A C T

Background and objective: The introduction of Paediatric NiTi instruments has transformed the field of paediatric endodontics. However, no studies are available on the mechanical behaviour of these files, wherein Finite Element Analysis (FEA) was found to play a major role. The objective of this study is to evaluate the mechanical behavior of three commercially available pediatric endodontic rotary file systems to bending and torsion stress analysis test through Finite Element Analysis (FEA).

Methods: A Finite Element Analysis study was performed on three commercially available pediatric endodontic rotary files (Pro AF baby, Kedo SG and Neoendo pedoflex) available for cleaning and shaping the narrow root canals of the deciduous teeth to bending and torsion tests with the boundary conditions according to ISO 3630-1 specifications.

Results: In the bending analysis, Pro AF baby files were found to withstand the complete bending tests without yielding with a maximum von Mises stress of 1366 MPa, and Kedo SG, Neoendo Pedoflex file exhibited maximum von Mises stress of 2296 MPa, 1971 MPa. Under torsion tests Kedo SG exhibited maximum stress distribution, while Neoendo Pedoflex and Pro AF baby files exhibited similar stress distribution.

Conclusion: Pro AF baby file effectively withstood the rigorous 45 -degree bending examination without experiencing yielding, while Kedo SG file exhibited higher flexibility. Under torsional resistance test, all the three instruments exhibited similar stress distribution under the yield limit. In summary, the mechanical behaviour (bending and torsion) of pediatric rotary file systems were influenced by design of the files.

1. Introduction

Pediatric endodontics is a crucial treatment modality that focuses on effectively removing debris and restoring the function of the pulpally affected primary teeth. Despite the extensive use of stainless steel hand files for debridement of deciduous teeth root canals, there are certain drawbacks which mainly include child's co-operation, increased duration of time and iatrogenic errors such as zipping, canal transportation, apical blockage.[1,2] The effectiveness of this procedure significantly depends on the chemo-mechanical preparation of the root canal system. Meticulous shaping of the root canals aids in removal of infected pulp tissue ensuring straight-line access for irrigation solutions to reach the apical region of the root, and facilitating proper filling of the root canals. However, the increased curvature of the root canal and the unique internal anatomy of the pulp cavity in primary teeth and features rarely seen in permanent teeth such as numerous ramifications, anastomosis involving furcations, accessory and secondary canals, it is difficult to achieve complete debridement of pulp remnants in primary teeth.[3] The introduction of rotary endodontics utilizing nickel titanium (NiTi) instruments in permanent teeth has led to a substantial enhancement in the realm of modern endodontic practice. However, in primary teeth, the utilization of these files has been restricted due to factors like the thinner root canal structure and a higher occurrence of lateral perforations.[2,4] With the purpose to avoid these adverse outcomes, exclusive Paediatric NiTi instruments were introduced[2–5] with improved features of clinical and radiographic success, less instrumentation time and post-operative pain.[6,7] The unintended separation of endodontic instrument is a potential complication that may arise during root canal instrumentation.[8,9] Primarily, these fractures occur when torsional or bending stresses surpass a certain threshold during use. Hence, torsion

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https://doi.org/10.1016/j.jobcr.2024.09.010
Received 19 July 2024; Received in revised form 23 August 2024; Accepted 17 September 2024

and bending are recognized as two crucial factors influencing the performance and safety of endodontic files, which were extensively studied in the rotary files systems used for permanent teeth.[9] However, there exists a paucity of literature regarding these properties in primary endodontic rotary file systems.

Root canal preparation using NiTi instruments in primary teeth was performed through use of endodontic rotary system designed precisely for permanent teeth prior to 2016.[10,11] Various studies have reported the clinical success of Profile, ProTaper, WaveOne, Mtwo, Hero 642, K3, Light Speed LSX and FlexMaster NiTi files rotary files used for permanent teeth in primary teeth.[5,12,13] The incidence of instrument failure of these files in primary teeth have also been recorded.[9] Nevertheless, variations in primary teeth root canal morphology led to the development of exclusive pediatric rotary file systems.[1,2] Though various studies have reported the cleaning and shaping efficacy of these files,[1–7] a few studies have reported the fracture incidence of these files through clinical and in-vitro studies.[14,15] The stress conditions within the instruments cannot be determined by post-fracture examination of separated files performed in vitro, wherein Finite Element Analysis (FEA) was found to play an vital role.[16]

FEA is a computational method that has been widely used in engineering to assess complex biomechanical properties of materials and has since been integrated in the field of Dentistry.[16–18] Though, it's use is underrated in the field of endodontics, it is proven to be pivotal in the assessment of various mechanical properties of these NiTi instruments by simulating the clinical conditions.[9,16] FEA analyses stress and deformations while addressing intricate structural challenges. Hence, FEA stands as a dependable analysis for appraising the performance of NiTi rotary instruments, enabling the testing of diverse instrument designs to the point of failure across a range of loading conditions.[9,16,17] This potential holds promise for curtailing both instrument development time and associated expenses.[16] Though various studies have evaluated the torsional and bending properties in rotary files used for permanent teeth through finite element analysis,[17–22] no studies have evaluated the mechanical behavior of the Pediatric rotary files under similar conditions. Pediatric rotary files differ from the rotary files used for permanent teeth such as unique design and smaller dimensions, specifically designed for the primary teeth which significantly impacts their performance and durability.[1,3,7] Furthermore, analysing the mechanical stressors such as bending and torsional force in these files will support in providing a comprehensive understanding of these instruments behavior, assisting in instrument selection, performance and safety, thus enhancing the clinical outcomes. Therefore, this study aimed to analyze and compare the mechanical behavior of three commercially available Pediatric endodontic rotary files used for cleaning and shaping the narrow canals of primary teeth through FEA, thereby providing valuable insight on their performance under bending and torsional stresses and aid in enhancing the design of these files.

2. Methodology

This study is reported according to the Reporting guidelines of in-silico studies using finite element analysis in medicine (RIFEM).[23]

2.1. Instruments analyzed

This is an in-vitro study involving computational simulation of endodontic instruments. Three commercially available pediatric endodontic rotary file systems employed for cleaning and shaping narrow canals in primary teeth were analyzed through Finite Element Analysis (FEA). The instruments evaluated to assess the bending and torsional fatigue included the Kedo SG Blue-D1 [#25, designed for narrow canals (Reeganz Dental Care Pvt. Ltd., India)] featuring variable taper, the Neoendo Pedoflex rotary file [#25 (red), 25/04 (Orikam Health Care, India)], and the Pro AF Baby files B2 (red) [#25–04 % (Dentobizz, India)]. These files comprised of Super-elastic controlled memory Nickel-Titanium (NiTi) alloys with triangular cross section. The total length of Kedo SG Blue – D1 and Neoendo, Pedoflex file (Red) was 16 mm with the active flute length of 12 mm, while the total length of Pro-AF Baby -B2 was 17 mm with the active working part being 13 mm.

2.2. Finite element model generation

2.2.1. Nano scanning process

All the three files were subjected to Nano scanning and analyzed using micro-CT scanner system (**Skyscan 2214**, Burker Kontich, Belgium) to capture the accurate shape and cross section of the files (Fig-1:a,b). The files were irradiated with an X-ray beam 90 k V and the camera resolution was fixed at a pixel size of 8. 50 μm. Scans were obtained by revolving the specimen at a degree rotation step obtaining 360° projection images and the cross-sectional geometries were determined.

2.2.2. Computer aided design (CAD) model generation

The computational model of the instruments were processed by assembling the cross sectional images of these files and a **Stereolithography model (STL)** of the files were generated. Three dimensional CAD model was developed (Fig-1:c,d) from the **DICOM (Digital imaging and computations in Medicine) images** obtained from STL files generated for all 3 rotary files using the **Solid Works 2021 Software** (Dassault Systèmes, SolidWorks Corp., Concord, MA, U.S.).

2.2.3. Finite element model generation

CAD models obtained were subjected to meshing process (Fig-1: e, f) with the **Hypermesh 14 Software** for the Finite Element model generation. The objective of the mesh generation was to ensure consistent element size for all three files. The element size was determined in a way that allowed for the application of identical loads across the three files. The final number of nodes and elements of the three finite element models were determined (Table 1).

2.3. Mathematical analysis

All the generated models were imported into **Abaqus 6.14 software**. The properties of these files were obtained in accordance to the study by Martins et al.2020[18] (Table-2) and were subsequently imported into the software.

2.4. Boundary conditions

The boundary conditions employed for simulating the behaviour of the endodontic instruments conformed precisely to the ISO 3630-1 specifications[19] (Fig. 2), as illustrated in Fig. 2.

2.4.1. Bending test

To analyze the bending resistance, NiTi instruments were fixed at 3 mm from the tip, effectively restricting any displacement along the three axes (X, Y and Z-axes). The handle of the instruments was subjected up to 20 mm displacement along the y axis to obtain an angle of 45°inclination and the free boundary condition was applied along the x and z axes.

2.4.2. Torsion test

To evaluate the torsion resistance, the endodontic instrument was secured 3 mm from the tip and a clockwise torsional moment of 0.3 Ncm was applied.

2.5. Static analysis

The mechanical properties were assessed with a focus on flexibility and torsional stress distribution. The stress patterns in the computational models were represented using von Mises equivalent stress. The

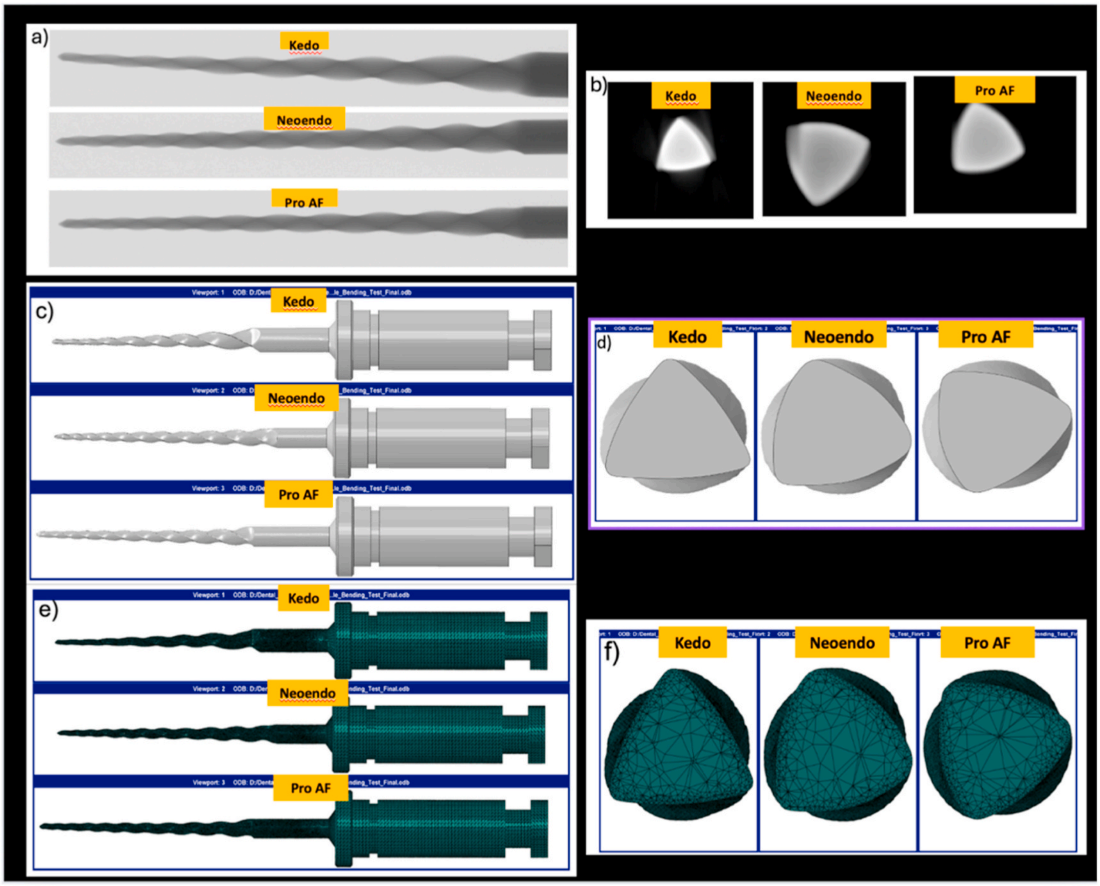

Fig. 1. (a), (b): Micro-CT Scanning Images of Kedo SG (D1), Neoendo Pedoflex, Pro AF baby (B2) rotary files. (c), (d): CAD Models (e), (f): Finite Element Mesh Model generation.

Table 1
– Number of nodes and elements in the finite element models.

File Name	No. of Nodes	No. of Elements
Kedo SG (D1)	179642	829156
Neoendo Pedoflex	178726	824060
Pro AF Baby (B2)	180068	818343

Table 2
–Parameters used to describe the consecutive models for simulation.

Parameters	Description	Value
A E	Austenite elasticity	55,737 MPa
A V	Austenite Poisson's ration	0.33
M E	Martensite elasticity	19,106 MPa
M V	Martensite Poisson's ration	0.33
ε^L	Transformation strain	8.6 %
σ_L^S	Start of transformation loading	448 MPa
σ_L^E	End of transformation loading	511 MPa
σ_U^S	Start of transformation unloading	161 MPa
σ_U^E	End of transformation unloading	118 MPa

resultant measurement of stress is represented as a color-coded figure.

3. Results

3.1. Bending test

Applying the displacement of 20 mm at 3 mm from the tip, each file passed through the 45-degree angulation following the specifications outlined in ISO 3630–1. The Kedo SG file demonstrated a maximum deflection angle of 52.18°, while the Neoendo file exhibited a deflection angle of 53.48°, and the Pro AF Baby file displayed a deflection angle of 49.85° (Fig. 3). Evaluation of stress distribution showed that maximum von Mises stress recorded was 2296 MPa, 1971 MPa, 1366 MPa for Kedo, Neoendo, Pro AF baby files respectively at 20 mm of displacement (Fig. 4: (a),(b)). Based on the bending force generated at each intervals of bending displacement, it can be concluded that Kedo SG file exhibited more flexibility when compared to Pro AF baby and NeoEndo files, respectively. Conversely, Neoendo pedoflex file exhibited had increased reaction force to bending suggesting increased internal resistance and reduced flexibility (Fig. 5: (a),(b)). This analysis indicates that the Kedo SG file exhibited less stiffness in comparison to both the Neoendo and Pro AF Baby files, respectively. When comparing the surface stress at the bending point where maximum stress was observed, PRO AF baby file-maintained stress levels within the yield limit, illustrating its capacity to withstand a complete bending test without experiencing yielding. Notably, it effectively withstood the rigorous 45-degree bending examination. Conversely, the Neoendo Pedoflex file demonstrated stress levels surpassing the yield limit, prompting yielding at a 14 mm displacement point and a bending angle of 34°. Similarly, in the case of the Kedo SG file, stress levels exceeded the yield limit, leading to yielding at a displacement of 14 mm and a bending angle of 33.5° (Fig. 5: (c)). Under the boundary conditions of the bending test, it was observed that the behavior of the Kedo and Neoendo files exhibited similarities. In contrast, the Pro AF Baby file displayed a more uniform stress distribution, without yielding which can be attributed to its file design.

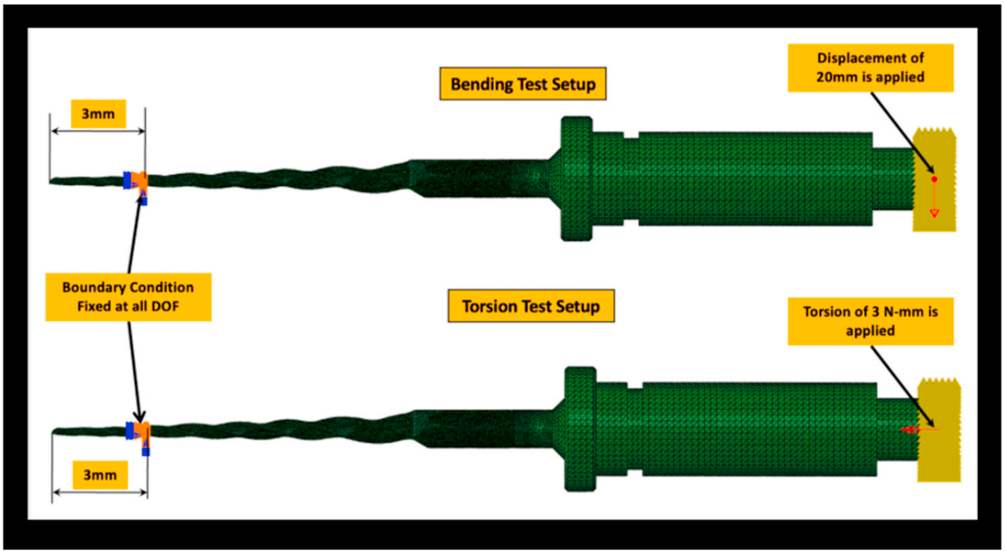

Fig. 2. Boundary conditions applied for bending and torsion tests.

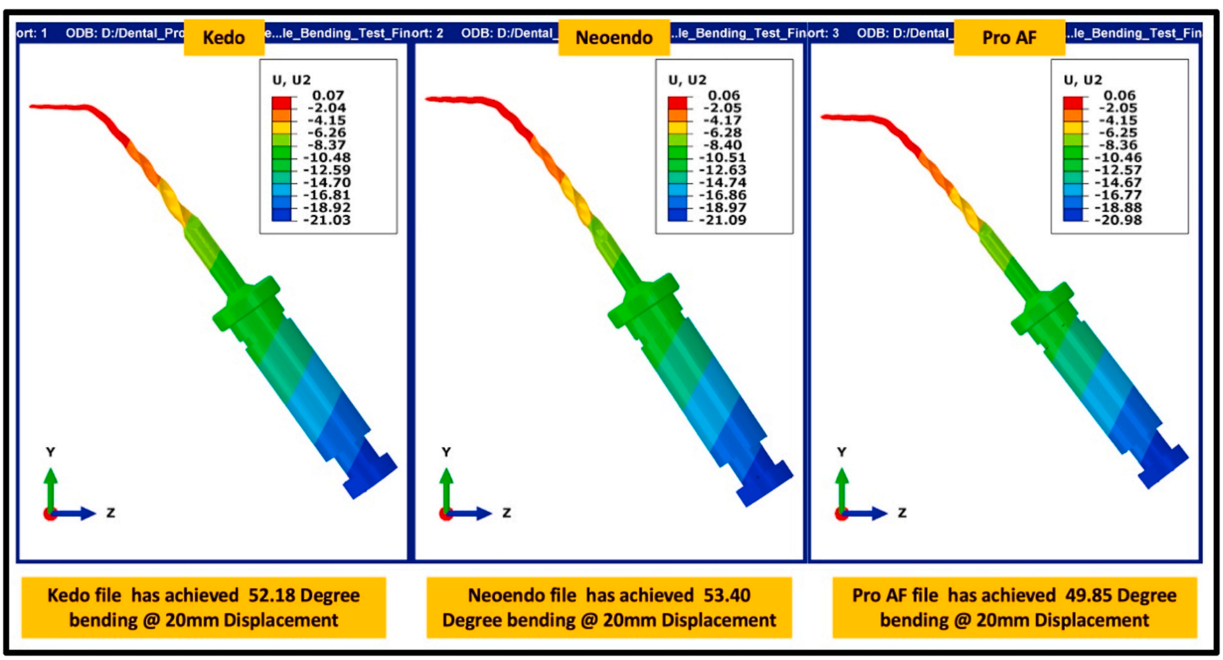

Fig. 3. Results of bending test analysis - von Mises stress distribution along the body at maximum bending displacement angle of Kedo SG, Neoendo Pedoflex and Pro AF Baby (B2) files.

3.2. *Torsion test*

The rotary files were subjected to a clockwise torsional force of 0.3Ncm at a point 3 mm from the file tip (Fig. 6: (a), (b) illustrates the comparison of von Mises stress among all three rotary file systems). Notably, the Pro AF Baby file exhibited a lower maximum stress distribution similar to the Neoendo and significantly less when compared to Kedo SG files. Upon analyzing the overall stress distribution across these files under torsional stress, it was observed that the stress patterns followed a similar trend and remained well below the yield limit for all three rotary files considered (Fig. 7).

4. Discussion

The fracture of NiTi rotary endodontic tools can be ascribed to the accumulation of repetitive compressive and tensile bending stresses at the critical stress juncture within a curved root canal is deemed the most undesirable complication.[10,25,27–29] A greater incidence of pediatric rotary file fracture in the narrower canals have also been recorded.[14,15] Studies on the post-fracture examination of the fractured NiTi rotary instrument in permanent teeth after clinical or simulated use did not reveal the intricate stresses endured by the instrument during bending or rotation,[16,24–27] wherein Finite Element Analysis (FEA) was found to play a pragmatic role.[9,16–23,29–33]

FEA is a repeatable method of biomechanical analysis that is conducted in silico and the intricate stress patterns within these endodontic files can be studied and analyzed. FEA outcome depends primarily on the precise quality of the computational models employed. To achieve accurate measurements of these intricate geometries, researchers have employed various methods including optical microscopes, profile

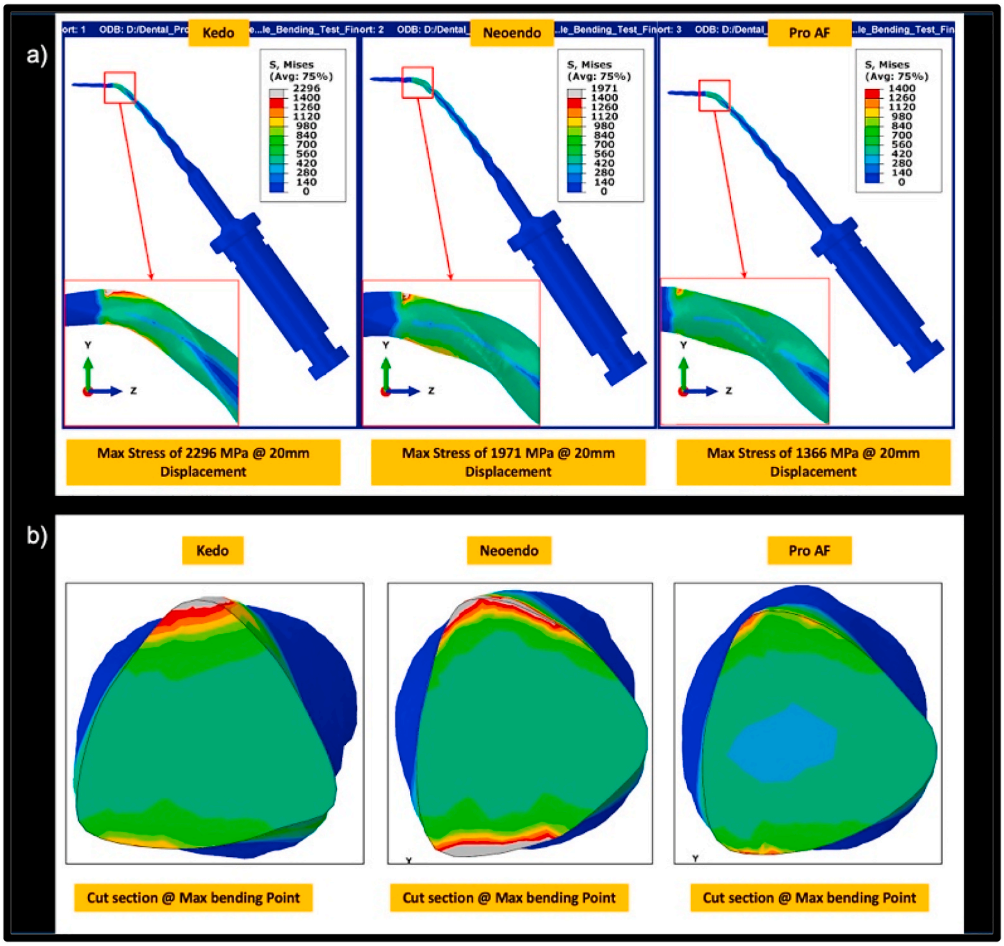

Fig. 4. Results of bending test analysis - (a): von Mises Stress Distribution at 3 mm from the tip. (b): von Mises maximum stress distribution cross section at 3 mm from the tip.

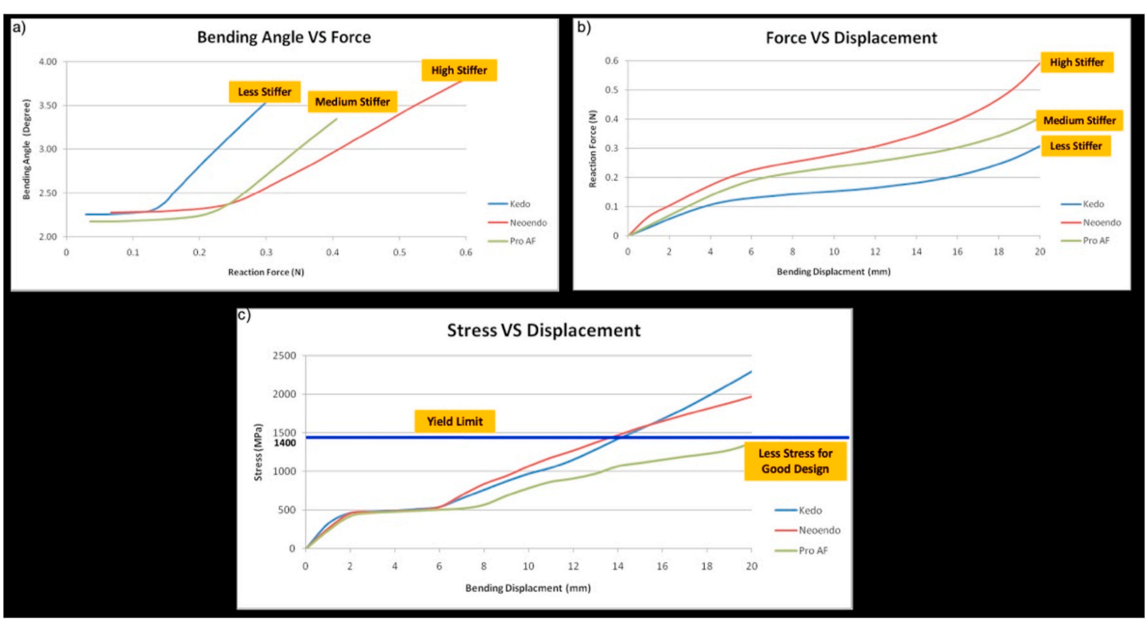

Fig. 5. Graph representing comparison of Kedo SG (D1), Neoendo Pedoflex and Pro AF Baby (B2) files to bending test. (a): The reaction force of files to the incremental bending angle (b): The reaction force generated during bending displacement. (c): The surface stress at bending point during bending displacement.

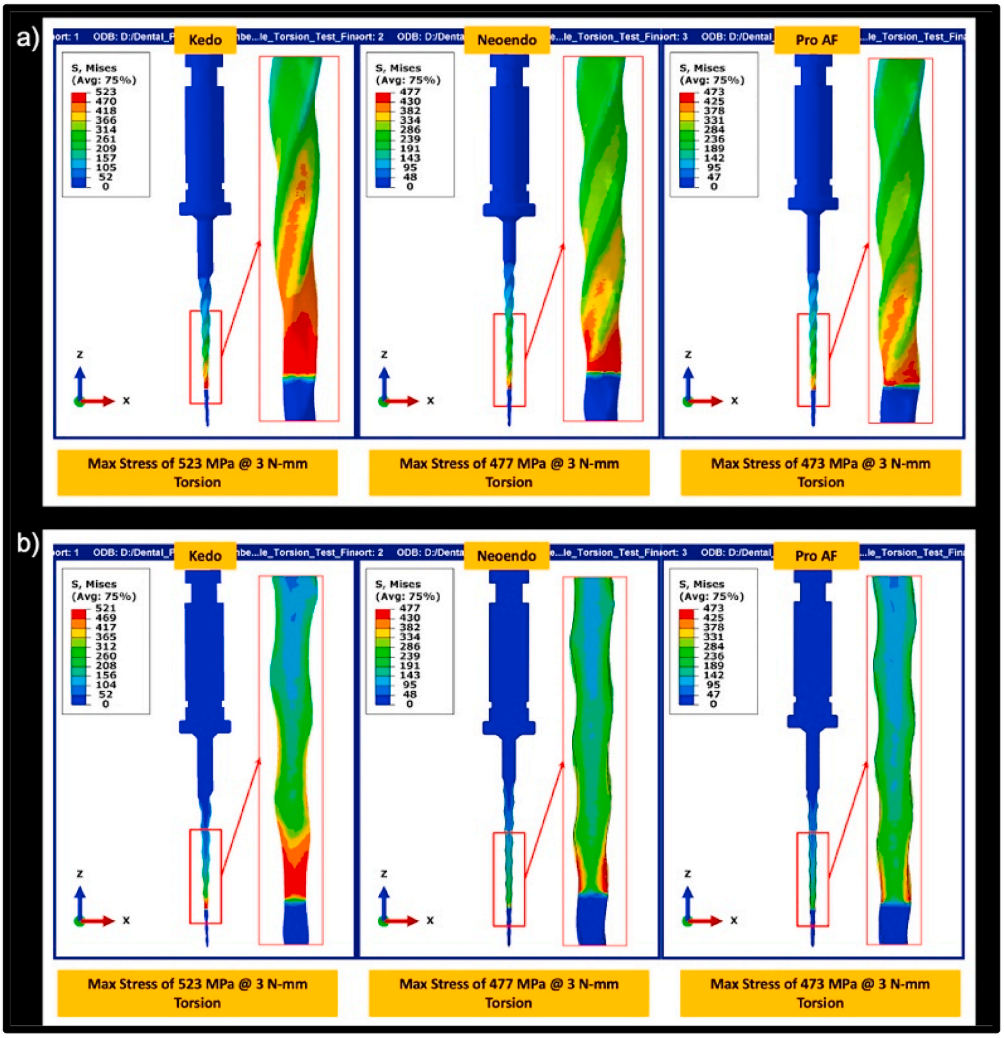

Fig. 6. Torsion test results (a): von Mises stress distribution of Kedo SG (D1), Neoendo Pedoflex and Pro AF Baby (B2) files to torsion test. (b): von Mises stress distribution (Cut-Section of three pediatric rotary files to torsion test at 0.3 Ncm.

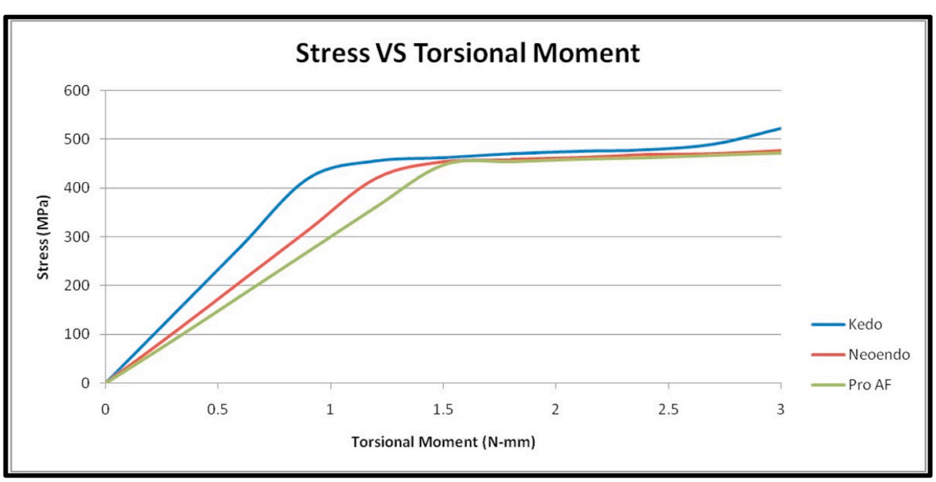

Fig. 7. Torsion test results: Graph representing the stress distribution to torsional moment.

projectors and Scanning Electron Microscopes.[16] In our study all the three rotary files considered were subjected to micro-CT scanning to capture the accurate shapes and cross section, and the final CAD- CAM models were generated, synonymous to previous studies.[20,29,31,32] Across the published studies various methods were proposed for the assessment of flexural and torsional fatigue, however there lacked a standardization for setting boundary conditions, where ISO 3630–1 provided a detailed description of modelling and procedure. This study analyzed the bending and torsional properties of three pediatric rotary files according to the ISO 3630-1 standards, which is in accordance to previous rotary file studies evaluated through FEA.[19–22,29,31,32] Though it is essential to consider potential variations arising from the manufacturing process, the potential variations in the mechanical properties were excluded due the lack in baseline data. The controlled memory material characteristics of the NiTi alloy were acquired from existing literature. A uniform consecutive model was developed with the mechanical properties obtained from literature according to Martinis et al., in 2020 for all instruments, considering the influence of geometry on torsional and flexibility stiffness.

A multitude of factors such as the flute length, taper, helix angle, mechanical characteristics, boundary conditions, stress application points, influenced the bending flexibility and torsional stiffness of endodontic files (specifically, V-Taper) were described by Kim et al., 2009, He and Ni 2010, using numerical simulations. The results of our study showed that the Pro AF baby file with increased flute length exhibited passive deformation without any yielding to the complete bending test of when compared to Neoendo and Kedo SG file. However, all the files exhibited higher surface stress near or at the cutting edge of all 3 instruments, suggesting that independent of the flute geometry (length), the tip section of the file was susceptible to damage which is in accordance to previous studies.[27,28,34] These studies also concluded that increase in the taper increases the stiffness of the file. Though all the three files considered in the present study had a similar taper of 4 %, Kedo SG file exhibited lesser stiffness when compared to Pro AF baby and Neoendo which can be ascribed to the Variably Variable taper (VVT) design incorporated in this file.[27,28] Based on this study's results, it can be computed that Kedo SG files are distinctly suitable for shaping the root canals with increased curvature due to their ability to navigate and adapt to complex canal paths. With its properties of increased flexibility, clinically it can be used where canal curvature presents with significant challenge. With respect to Pro AF baby, which was able to withstand the force without any yielding, it can be concluded these files are better suited for clinical scenarios where additional force is required for negotiating the canals such as calcified, narrower or constricted canals. Their design favours towards to application greater force, which is advantageous for achieving optimal canal preparation in more impervious or constricted areas.

Torsional stiffness refers to a material ‘s or object ‘s capacity to resist twisting under the action of an applied torque, was evaluated in this study by examining the stress distribution of the pediatric rotary files considered under similar torsional moment. It was observed that Neoendo and ProAF exhibited a similar and lower level of stress distribution, 477Mpa and 473 MPa respectively when compared to Kedo SG where maximum stress distribution of 523 MPa was evident. Not a single rotary file analyzed, demonstrated the properties of higher flexibility, ability to withstand and distribute stress equally under bending and torsion. This could be attributed to the variable properties such as cross-sectional design, pitch, concentricity of the cross section, taper, metallurgy, off-center design of the file, different elastic moduli and dentine canal rigidity each of which influences the fracture sensitivity of the rotary instruments.[9,21,22,27,28,32–35]

The results of our study showed that the length of the file and taper of the file influenced the bending and torsional resistance which was in accordance to previous studies evaluated on rotary files in permanent teeth.[27,28] However, other factors such as cross sectional design, area and mechanical characteristics were similar, in accordance to manufactures, in the three files evaluated. While various cross-sectional designs have been developed for rotary files used in permanent teeth, pediatric rotary files have conventionally featured a triangular cross-section, this was a comparative study on the existing pediatric rotary file systems with no other experimental conditions applied to these files.

Research indicates that several factors, including instrument design, canal curvature assessment, proper access preparation, canal orifice enlargement, manual instrumentation, rotational speed and torque settings, cleaning and shaping techniques, rotary instrument handling, and operator skill, have influenced the prevention of NiTi rotary instrument fracture in permanent teeth. Based on these findings, a thorough preoperative assessment of root canal of primary teeth for the degree of curvature and calcification using periapical radiographs, along with manual instrumentation, can guide the selection of appropriate rotary instruments based on the clinical scenario. Furthermore, calibrating the rotational speed and torque according to manufacturer recommendations and ensuring adequate training in the use rotary instrument for primary teeth such as use of the instrument in an “in and out motion” within well lubricated canals can help prevention of deformation and separation.[25,26]

With the manufacturers recommendations available, the results of the study also align with common clinical practices and literature evidence available for similar instruments. The instruments analyzed were used for cleaning and shaping narrow canals of the primary teeth as per the manufactures recommendations with increased curvature such as the mesiobuccal and distobuccal canals of the maxillary molars with incidence of fracture in literature.[14] With the instruments analyzed according to the ISO 3630-1 standards, the results of our study align with manufacturer recommendation, such as increased flexibility of the Kedo SG file, and improved stress efficiency of Pro AF baby files when compared to Nedoendo Pedoflex files.

The limitations of the current study can be attributed to the drawbacks inherent in the linear FEA method, which can be succinctly summarized as follows: (A) The boundary conditions examined in this study rarely replicated clinical scenarios. Nevertheless, they may offer valuable insights into comprehending the behavior of shape memory alloys, (B) In order to maintain consistency, the model was subjected to simulation using uniform mechanical properties.

Based on the current literature, this is the first study to assess and compare the commercially available pediatric rotary file systems to mechanical stress such as bending and torsional stress through FEA. This study lays a foundation for future finite element studies in pediatric rotary files with improved mechanical and geometric properties through experimental conditions which would aid in the development of redefined files with enhanced designs in pediatric rotary file systems.

5. Conclusion

Under controlled conditions of FEA study conducted on the three Pediatric rotary files it can be concluded that.

1. Pro AF baby file effectively withstood the rigorous 45 -degree bending examination without experiencing yielding with the lowest stress value indicating its longer fatigue life.
2. Kedo SG file exhibited higher flexibility when compared to other instruments. This instrument exhibited a reduced reaction force at each interval of bending displacement, subjected to bending up to 45-degree angulation.
3. Under torsional resistance test, all the three instruments exhibited similar stress distribution under the yield limit, however Kedo SG file presented with maximum stress distribution at 0.3 Ncm.

Ethical approval

This study was approved by the Institutional Ethics committee (REF NO: CSP/23/JUN/130/533).

Sources of funding

This research has been approved by the ISPPD – Indian Society of Pedodontics and Preventive Dentistry- Research Assistance Grant-2022 and the final report has been submitted for release of grant amount (Rupees Ten Thousand). As on the date of submission of the manuscript, no funding was received to assist with the preparation of this manuscript.

Author contributions

Harshinie M: Conceptualization; Methodology; Investigation; Funding acquisition; Resources; Writing - original draft; Validation.

Selvakumar H: Conceptualization; Supervision; Methodology; Investigation; Funding acquisition; Resources; Writing – review and editing; Validation.

Vignesh KC: Conceptualization; Supervision; Methodology; Investigation; Funding acquisition; Resources; Writing – review and editing; Validation.

Kavitha Swaminathan: Conceptualization; Supervision; Methodology; Investigation; Funding acquisition; Resources; Writing – review and editing; Validation.

Declaration of competing 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.

Acknowledgements

We sincerely thank Whitelab-Material Research Cente, Saveetha Dental College and Hospital for their assistance with the micro-CT scanning process and Mr. Ramkumar Murugan, CAE specialist, for helping us with the finite element model set up and analysis.

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