Journal of Oral Biology and Craniofacial Research 15 (2025) 310–318

Contents lists available at ScienceDirect

Journal of Oral Biology and Craniofacial Research

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

Evaluation of cyclic fatigue in three pediatric endodontic rotary file systems in root canals of primary molars: A finite element analysis (FEA)

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A R T I C L E I N F O

Keywords:
Cyclic fatigue
Pediatric rotary files
Finite element analysis (FEA)
Primary molars
Endodontics

A B S T R A C T

Objective: The aim of this study was to evaluate the cyclic fatigue resistance of three different pediatric endodontic rotary files in the root canals of primary molars using finite element analysis (FEA). The research focuses on understanding the mechanical behavior of the files under varying canal curvatures to determine their suitability for pediatric endodontics.
Methods: Finite Element Analysis (FEA) was utilized to simulate cyclic fatigue performance in primary molar canals with curvatures of 30°, 60°, and 90°. The rotary files made up of nickel-titanium (NiTi) alloys included in this study were Kedo SG, Neoendo Pedo Flex, and Pro AF Baby. Stress distribution, maximum stress values, and cyclic fatigue resistance were evaluated to identify differences in performance. Simulations were conducted under controlled conditions to model real-world clinical scenarios. Stress distribution and the number of cycles until failure were analyzed using Goodman's fatigue model and the S-N curve.
Results: The Pro AF Baby files exhibited the highest cyclic fatigue resistance and the more favourable stress distribution across all canal profiles, due to its triangular cross-sectional geometry. Whereas, Kedo SG and Neoendo Pedo Flex demonstrated higher stress levels and lower fatigue life, particularly in severe curvatures (90°), indicating increased susceptibility to failure. Elevated stress concentrations were observed near the apical tip, correlating with reduced fatigue life as canal curvature increased.
Conclusion: Pro AF Baby B2 demonstrated better fatigue resistance and safety for endodontic procedures in primary molars with complex root canal curvatures. These findings emphasize the importance of material properties and file design in improving clinical outcomes. Future research should focus on long-term clinical validation and further optimization of rotary file systems for pediatric dentistry.

1. Introduction

Endodontic treatment in pediatric dentistry presents unique challenges due to the anatomical complexities of primary teeth, such as thinner dentinal walls and curved root canals.[1–3] The introduction of nickel-titanium (NiTi) endodontic instruments has addressed these difficulties by offering more flexibility compared to traditional stainless-steel instruments.[4–6] Technological advancements have further led to the development of NiTi rotary files, specifically designed to navigate the complex anatomy of primary molars. These rotary files offer advantages over traditional hand files, including reduced procedure time and improved clinical outcomes.[2,7] Despite these improvements, cyclic fatigue remains a major concern, where the NiTi endodontic files are prone to unexpected fractures during repeated cycles of tension and compression within curved canals, impacting their durability and safety.[8]

Barr et al. (2000) were the first to demonstrate the use of NiTi rotary files in primary molars.[6] Pediatric rotary files have significantly reduced treatment time and improved canal cleaning efficiency, making them particularly beneficial for managing younger patients.[7,9] However, the risk of instrument fracture within the root canal remains a considerable challenge, primarily attributed to torsional overload or cyclic fatigue.[10] Ashkar et al. evaluated the impact of continuous rotation versus reciprocating motion on different rotary instruments, revealing that reciprocating motion provides higher cyclic fatigue resistance. Importantly, file separation can occur without visible signs of permanent

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https://doi.org/10.1016/j.jobcr.2025.01.023
Received 28 November 2024; Received in revised form 20 January 2025; Accepted 23 January 2025

deformation, even within the elastic limit of the instrument. Thus, visible inspection alone is an unreliable method for addressing the integrity of NiTi instruments.[11]

Finite element analysis (FEA) has emerged as a valuable tool for evaluating the mechanical behavior of NiTi rotary files. Through stress and strain simulations, FEA provides a deeper understanding of the factors contributing to fatigue and highlights potential opportunities for design improvements.[12–14] However, research specifically focused on pediatric rotary files remains scarce, leaving gaps in knowledge regarding their performance in clinical conditions.[7–9]

This study aims to address these gaps by assessing the cyclic fatigue resistance of pediatric rotary files used in primary molars through FEA. The results aim to provide clinicians with evidence-based guidance for selecting appropriate instruments, thereby enhancing the safety and effectiveness of pediatric endodontic treatments. Moreover, the findings could contribute to the development of more durable and efficient rotary systems, advancing pediatric endodontics and improving outcomes for young patients.

2. Materials and methods

2.1. Ethical approval

This study was approved by the Institutional Ethics Committee (CSP-III/24/SEP/11/406).

2.2. Analysis of endodontic instruments

This study was conducted within the framework of FEA, wherein various pediatric endodontic rotary files and root canal geometries were surveyed.

It evaluated three different pediatric endodontic rotary files: Kedo SG Blue-D1 (#25, Reeganz Dental Care Pvt. Ltd., India), Neoendo Pedo Flex rotary file (#25 red, 25/04, Orikam Health Care, India), and Pro AF Baby files B2 (red, #25, 04 %, Dentobizz, India). The comparative analysis focused on key differences in their performance and application.

The files are produced from NiTi alloys, known for their superelastic and controlled-memory properties. The Kedo SG Blue-D1 and Neoendo Pedo Flex files have a total length of 16 mm, with an active flute length of 12 mm. Meanwhile, the Pro AF Baby B2 has a total length of 17 mm and an active working section of 13 mm. During the analysis, the root canal is modeled as a rigid, immovable surface.

2.3. Finite element model geometrical models

Nano-scanning of the three files was performed, followed by the acquisition of high-resolution images of their shape and cross-sections using a micro-CT scanner system (Skyscan 2214, Bruker Kontich, Belgium).

The cross-sectional images and corresponding STL models of each file were then incorporated into the development of computational models for the instruments.

Further, CAD geometrical models were created to approximate the actual files, including key characteristics such as variable taper and triangular cross-sectional geometry [Fig. 1: a, b]. These features were intended to enhance flexibility and cutting efficiency.

2.4. Mesh

Three-dimensional CAD models were developed from the DICOM images obtained from the STL files of all three rotary files using SolidWorks 2021 software (Dassault Systèmes, SolidWorks Corp., Concord, MA, U.S.). These geometric CAD models were then meshed with Hypermesh 14 software to create the finite element model [Fig. 1: c, d].

2.5. Node and element details for FEM

The objective for generating the mesh was to ensure uniform load application across all three files, with consistent sizes. The final number of nodes and elements for each of the three finite element models is presented in [Table- 1].

Table 1
Number of nodes and elements of the Files.

File name	No. of Nodes	No. of Elements
Kedo	179642	829156
Neoendo	178726	824060
Pro AF	180068	818343

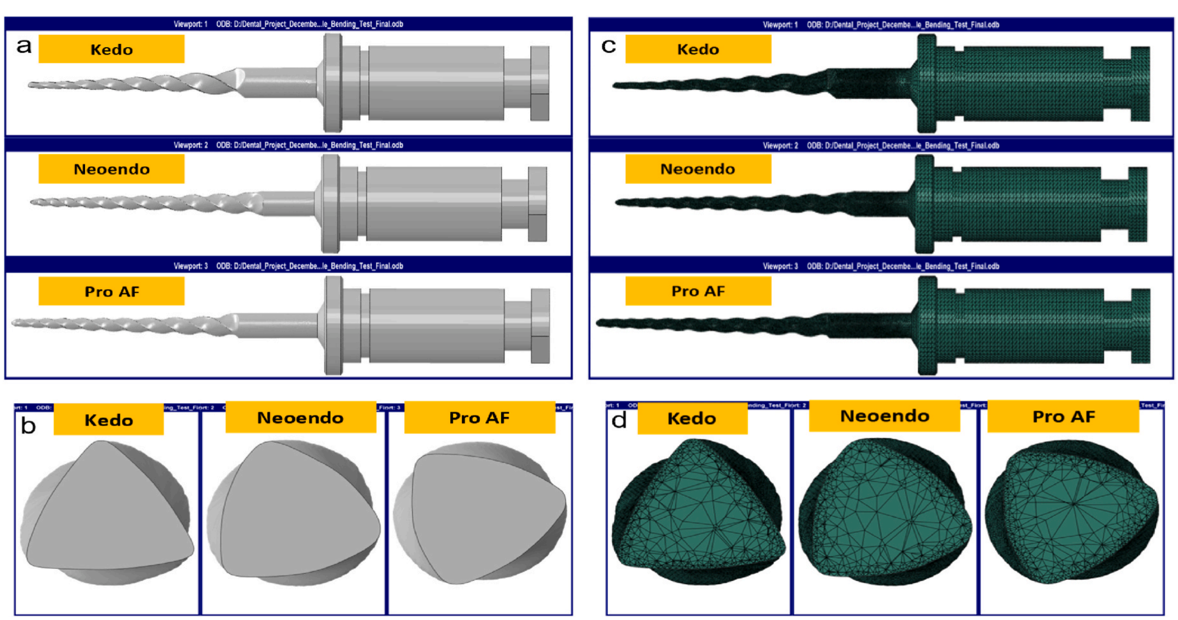

Fig. 1. (a), (b): CAD Models Kedo SG (D1), Neoendo Pedoflex, Pro AF baby (B2) rotary files. (c), (d): Finite Element Mesh Model generation.

2.6. Material properties and mathematical analysis

These simulation models were imported into Abaqus 6.14 software. The material properties used for the simulation were adopted from Martins et al. (2020) and subsequently loaded into the software, as shown in [Table- 2]. Auricchio's material model was applied to simulate the superelastic behavior of NiTi alloy, with EA and EM representing Young's modulus of austenite and martensite, respectively. The mechanical behavior of NiTi files was numerically analyzed using Abaqus 6.14 software to simulate and measure their cyclic fatigue performance.

2.7. Boundary conditions

The mechanical interaction between the root canal and the endodontic rotary file was modeled as a node-to-surface contact. The boundary conditions used to simulate the behavior of the endodontic instruments strictly conformed to the ISO 3630-1 specifications [Figure- 2]. The insertion of the endodontic rotary file was represented by applying a displacement to its reference node along the y-axis, with a magnitude equal to the active length of the file. Subsequently, the file was rotated 360° along the axis of rotation while constraining all the other movements of the reference node, including the rotations about the x and z axes and other displacements. The study aimed to predict the fatigue life of NiTi rotary files during rotation within a root canal. To achieve this, the NiTi instrument handle was placed 9 mm from the tip, effectively constraining movement along the X, Y, and Z axes. Furthermore, the mechanical properties were evaluated based on the distribution of maximum stress, with the stress values represented by a colored figure. The fatigue life of the rotary file was determined by identifying the number of cycles to failure to the node exhibiting the least fatigue life on the file's surface.

3. Results

3.1. Profiles of root canal

Stress and displacements were measured at angles of 30°, 60°, and 90° [Figure- 3] representing varying degrees of canal curvature to simulate various clinical conditions encountered by rotary endodontic files. The 30° angle corresponds to slight curvature with minimum stress, 60° reflects moderate curvature with intermediate stress levels, and 90° represents severe curvature associated with maximum stress and strain on the files [Figure- 4 (a) (b) (c)]. These angles were selected to evaluate the incremental effects of canal curvature on stress distribution and fatigue life. This approach ensures that study conditions represent a wide range of clinically realistic scenarios. Thus, by considering these profiles, this study seeks to enhance understanding of rotary file performance across different geometries, improving the reliability of fatigue-life predictions and supporting valid conclusions for endodontic practice.

Table 2
Parameters used to describe the constitutive model for stimulation.

Parameter	Description	AR
E_A	Austenite elasticity	55,737 MPa
V_A	Austenite Poisson's ratio	0.33
E_M	Martensite elasticity	19,106 MPa
V_M	Martensite Poisson's ratio	0.33
ϵ^L	Transformation strain	8.6 %
$(\delta\sigma/\delta T)_L$	(δσ/δT) loading	6.7
σ_L^S	Start of transformation loading	448 MPa
σ_L^E	End of transformation loading	511 MPa
T_0	Reference temperature	25 °C
$(\delta\sigma/\delta T)_U$	(δσ/δT) unloading	6.7
σ_U^S	Start of transformation unloading	161 MPa
σ_U^E	End of transformation unloading	118 MPa

3.2. Stress analysis results

This study aimed to evaluate the stress distribution and maximum stress values of three endodontic rotary files—Kedo, Neoendo, and Pro AF—using FEA against the canal profiles with varying curvatures of 30°, 60°, and 90° (Table- 3). The analysis showed that increased curvature causes greater stress concentration near the file tip. In highly curved canals, this heightened stress is likely to increase the file's susceptibility to fatigue and potential fracture. Following comparisons show that maximum stress values progressively increase with the canal angle [Figure-5a].

- 30° Canal Profile: Lower stress levels were observed, with the Pro AF pedodontics file exhibiting the minimum stress value of 420 MPa. Neoendo files recorded a stress of 449 MPa, while Kedo files showed 485 MPa. The stress distribution is displayed graphically by cooler colors, such as blue and green, as depicted in (Fig. 6a).
- 60° Canal Profile: Moderate stress levels were noted, with Pro AF files demonstrating the lowest peak stress value of 857 MPa. Neoendo files showed a value of 967 MPa, whereas Kedo files displayed a significantly higher value of 1578 MPa, showing more noticeable stress regions in warmer colors (Fig. 6b).
- 90° Canal Profile: Maximum stress levels were identified as 2022 MPa for Pro AF files, 2481 MPa for Neoendo files, and 4063 MPa for Kedo files. Notable red zones near the file tip indicate regions of elevated stress. These results confirm that canal curvature significantly influences both the durability and performance of the file (Fig. 6c).

3.3. Fatigue analysis results

The stress-based approach is extensively applied to analyze materials subjected to repeated loading. Fatigue properties were evaluated using this approach in conjunction with the Normal Stress Goodman algorithm to compare the fatigue life of these materials under operational loads. This algorithm effectively predicts fatigue failure by accounting for both alternating or fluctuating and mean stresses, making it ideal for materials exposed to varying loads.

The analysis focused on key parameters, including the endurance limit of 2nf at 2×10^7 cycles, implying that the files subjected to stress levels below this threshold will withstand at least this many cycles (Table 4).

Young's Modulus (E) was measured at 55,737 MPa, reflecting the material stiffness and its capacity to elastically deform under load.

Larger stiffness corresponds to reduced elastic deformation, which is critical for rotary files as it determines their response to stress within curved canals.

A Poisson's ratio of 0.33 and ultimate tensile strength (UTS) of 600 MPa were also considered, with the latter representing the maximum stress the material can endure before breaking.

In fatigue analysis, the UTS serves as an upper limit for stress amplitude in Goodman's algorithm, aiding in defining safe operating conditions. The stress-number (S-N) curve, which illustrates the relationship between cyclic stress and the number of cycles to failure (NCF), was employed in this study (Fig. 5b). Fatigue characteristics were modeled using an S-N curve with specified values of 600 MPa at 100 cycles and 200 MPa at 100,000 cycles. This curve is instrumental in predicting fatigue life at different stress levels, providing insights into material endurance under various loads. The fatigue analysis included conditions ranging from no-load (unstressed state) to operational load (when the file is actively working within the canal). This approach captures the full range of stresses the file encounters during clinical use, from minimal to applied operational loads. This approach ensures a detailed understanding of the file's fatigue behavior under varying stress conditions, providing more accurate predictions of its failure under repeated use.

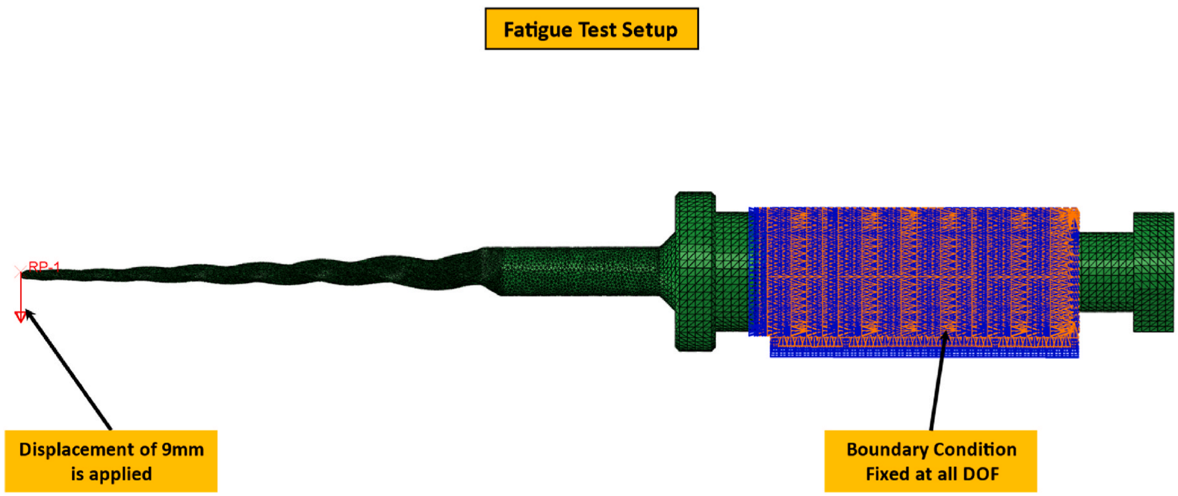

Fig. 2. Loading and Boundary condition.

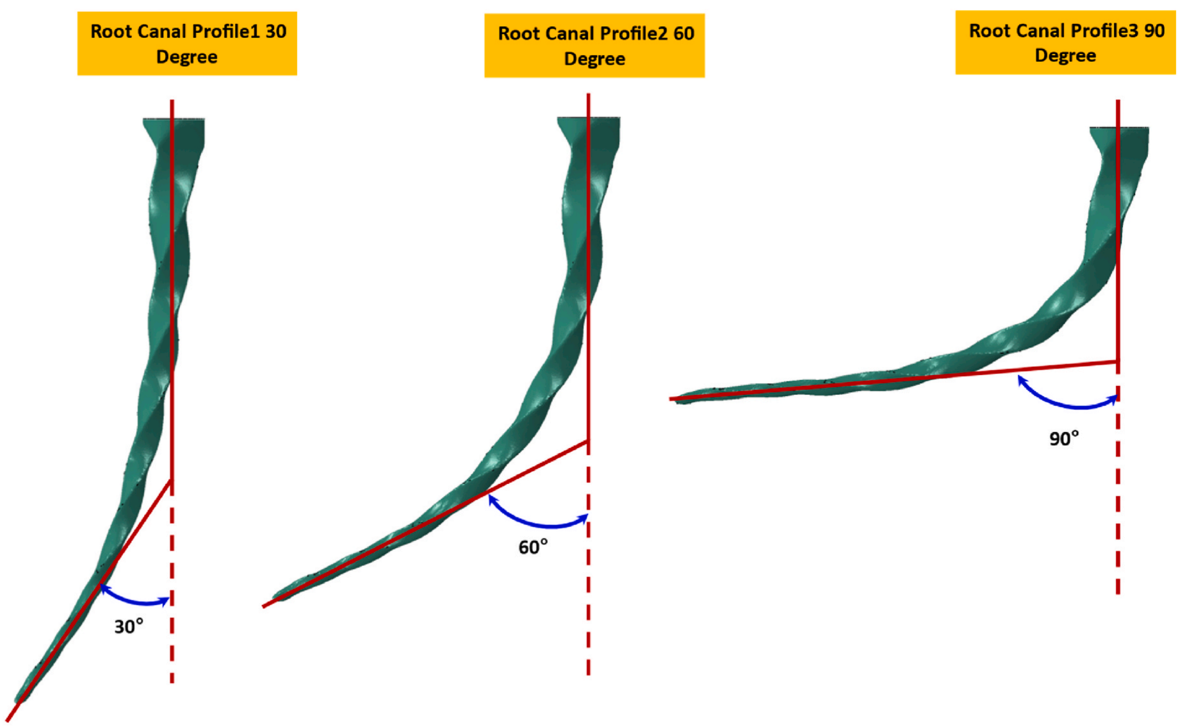

Fig. 3. Different types of root canal angulation considered to validate each file to predict the fatigue cycle.

3.4. Comparison of number of cycles for each rotary files

The fatigue failure cycles were tested for each type of file with respect to canal profiles [Fig. 7a, b, 7c] The results revealed the following:

- The Pro AF file showed significantly higher cyclic endurance, especially in 90° canals, indicating greater resistance to fatigue.
- The Neoendo and Kedo files exhibited a decrease in cycles to failure as canal curvature increased, suggesting higher susceptibility to fatigue with sharper curvatures.

Overall, the comparison showed that the Pro AF constantly presented a lower stress level across all canal profiles, resulting in a longer fatigue life. This design and material choice enhance its suitability for curved canals, reducing the odds of fractures in complex root canal systems.

These results position the Pro AF as a safe and reliable alternative for procedures involving a high degree of canal curvature, as it minimizes the probability of file separation and increases the safety level.

4. Discussion

In pediatric dentistry, the use of rotary NiTi instruments raises concerns primarily due to cyclic fatigue, which is responsible for up to 70 % of instrument fractures, with the remaining attributed to torsional fatigue.[15,16] These fractures mostly occur in curved canals, where rotary files undergo repeated tensile and compressive stresses. In primary molars, these stresses are intensified due to narrower and tortuous root canal.[17,18] Cyclic fatigue is a significant concern with rotary endodontic instruments, as the file experiences repeated tension and compression within root canals, eventually leading to breakage.[17] Visible signs of wear, such as unwinding flutes, are often unreliable, so clinicians must

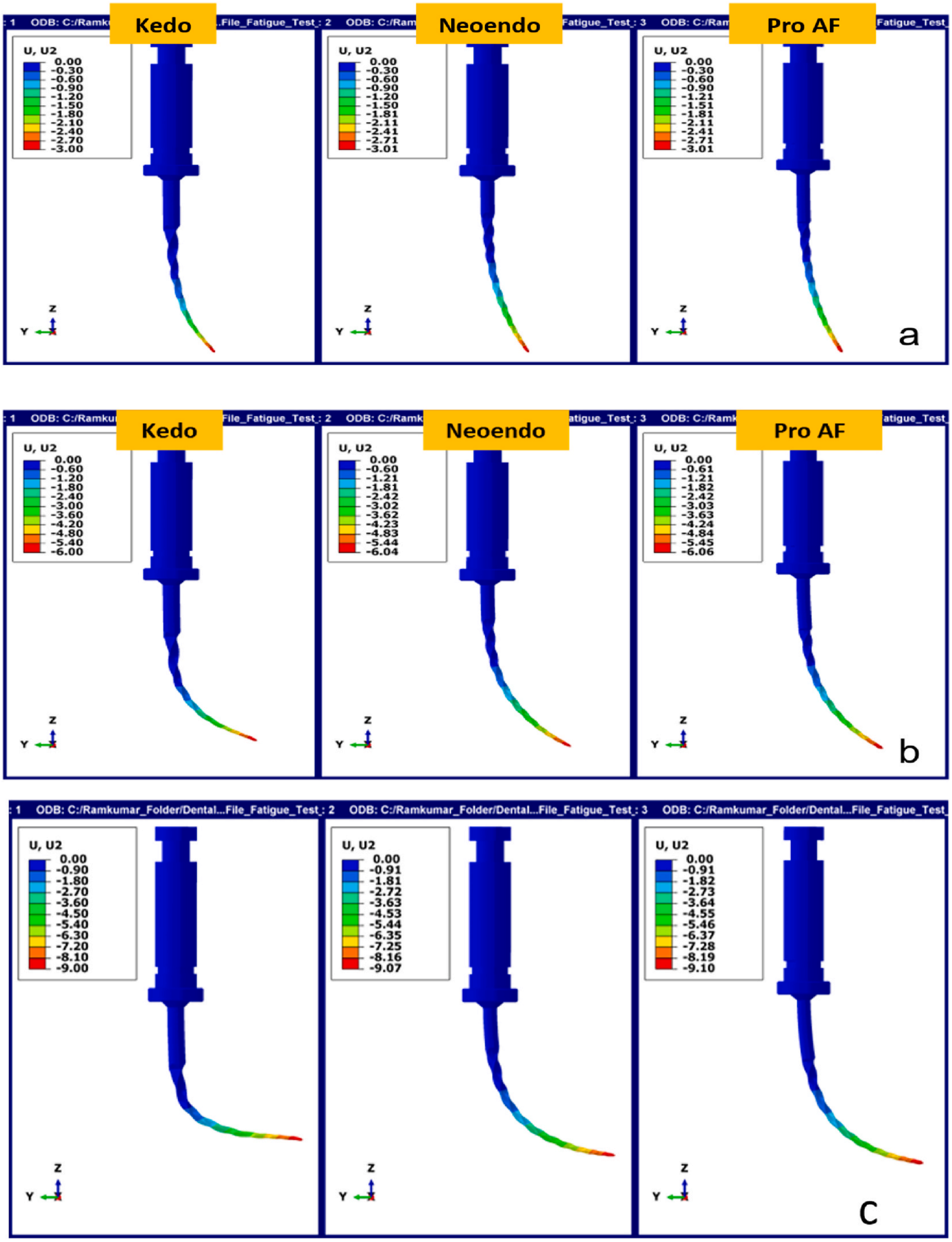

Fig. 4. Fatigue test – displacement comparison at (a) 30°, (b) 60° and (c) 90°.

Table 3
Max Stress Value of Stress analysis.

S.No	Root canal angle (Degree)	Max Stress (MPa)		
		Kedo	Neoendo	Pro AF
1	30	485	449	420
2	60	1578	967	857
3	90	4063	2481	2022

rely on their understanding of how instruments respond to stress and fatigue. Opting for high-quality files made from advanced materials like heat-treated nickel-titanium (NiTi) can significantly lower the risk of failure. Additionally, limiting file reuse and ensuring adequate canal lubrication are essential steps to prevent fractures. With thoughtful planning and the right tools, clinicians can deliver safer and more effective treatments, even in complex cases.

The current study evaluates the cyclic fatigue of three rotary files by using FEA simulations on different root canal curvatures. FEA is a computational method widely employed in engineering and biomedicine to simulate mechanical behavior under diverse conditions. In dentistry, especially in endodontics, it serves as a valuable tool for evaluating the mechanical performance of rotary file systems by assessing their stress, strain, and deformation.[19,20] This approach involves developing a digital model of the rotary file under investigation, which is subdivided into a mesh system consisting of finite elements

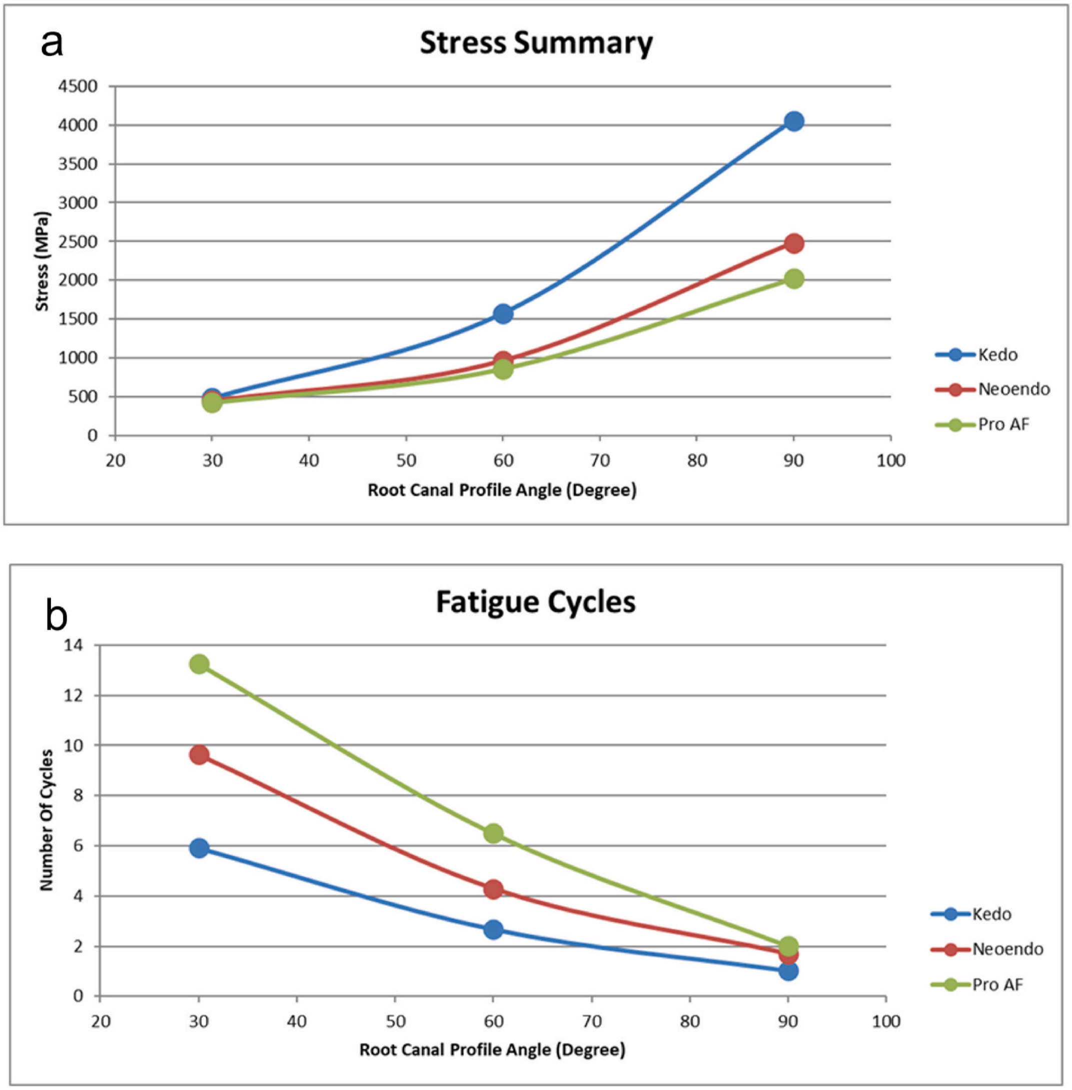

Fig. 5. (a) Max Stress Comparison Graph of Stress analysis (b) Max Stress Comparison Graph of Fatigue analysis.

interconnected by nodes. The software applies equations of motion and material properties to calculate the response of each element. This facilitates understanding the behavior of rotary files under cyclic fatigue and torsional conditions generally present during root canal procedures.[21,22] Unlike other experimental methods, FEA provides a controlled testing environment that removes variability from operator technique, ensuring high repeatability along with precision in stress and fatigue life.[19,20] Additionally, FEA enables simulation without destroying the test files, making it particularly suitable for iterative design optimization.[22] FEA generates an image representing specific locations of stress concentrations or deformation patterns, aiding in the assessment of the effect of cross-sectional geometry and material properties on performance.[20,22] This study examined three pediatric rotary file systems: Kedo SG Blue-D1, Neoendo Pedo Flex rotary file, and Pro AF Baby files B2. Simulations were performed on primary molar canals with curvature angles of 30°, 60°, and 90°, replicating clinical scenarios. Among all files, 90° curvatures consistently exhibited the maximum stress concentrations, predominantly near the apical tip. These results support earlier reports indicating that higher curvature leads to increased bending stresses, thereby raising the likelihood of fatigue failure.[20,22]

Notably, Pro AF exhibited the lowest stress concentrations and the highest resistance to cyclic fatigue among the tested files. Its superior performance is attributed to its triangular cross-sectional geometry, which minimizes stress accumulation while maintaining excellent cutting efficiency. This finding aligns with previous studies highlighting the significance of cross-sectional geometry in enhancing fatigue resistance and promoting efficient debris removal.[20] In contrast, Neoendo and Kedo files showed higher stress levels in curved canals, indicating the need for design refinements to improve flexibility.

Chi et al. (2016) compared the cyclic fatigue resistance in artificial root canals using two rotary files: ProTaper F2 and ProFile (#25.04). Their results showed that ProFile demonstrates superior fatigue resistance than ProTaper, mainly due to differences in cross-sectional geometry and taper.[18] Fatigue life is inversely correlated with the extent of curvatures and the smallest radii in the canals. Files initially subjected to low strain display longer survival time compared to those directly subjected to higher strain. Besides, heat treatment plays a critical role in enhancing the performance of NiTi rotary files by stabilizing the martensitic transformation phase, which increases flexibility and cyclic fatigue resistance. This treatment allows the files to sustain a high degree of alternating stress without fracturing.[19,22] Additionally, heat treatment refines the microstructure of NiTi, improving stress distribution around its surface and reducing the risk of potential failure.[20,21] Abdellatif et al. (2024) reported that the incorporation of heat-treated NiTi alloys into endodontic procedures enhances the cyclic fatigue resistance of rotary files for safer and less time-consuming root canal procedures. The study further highlighted that instruments fabricated from advanced alloys such as M-wire and CM-wire show superior

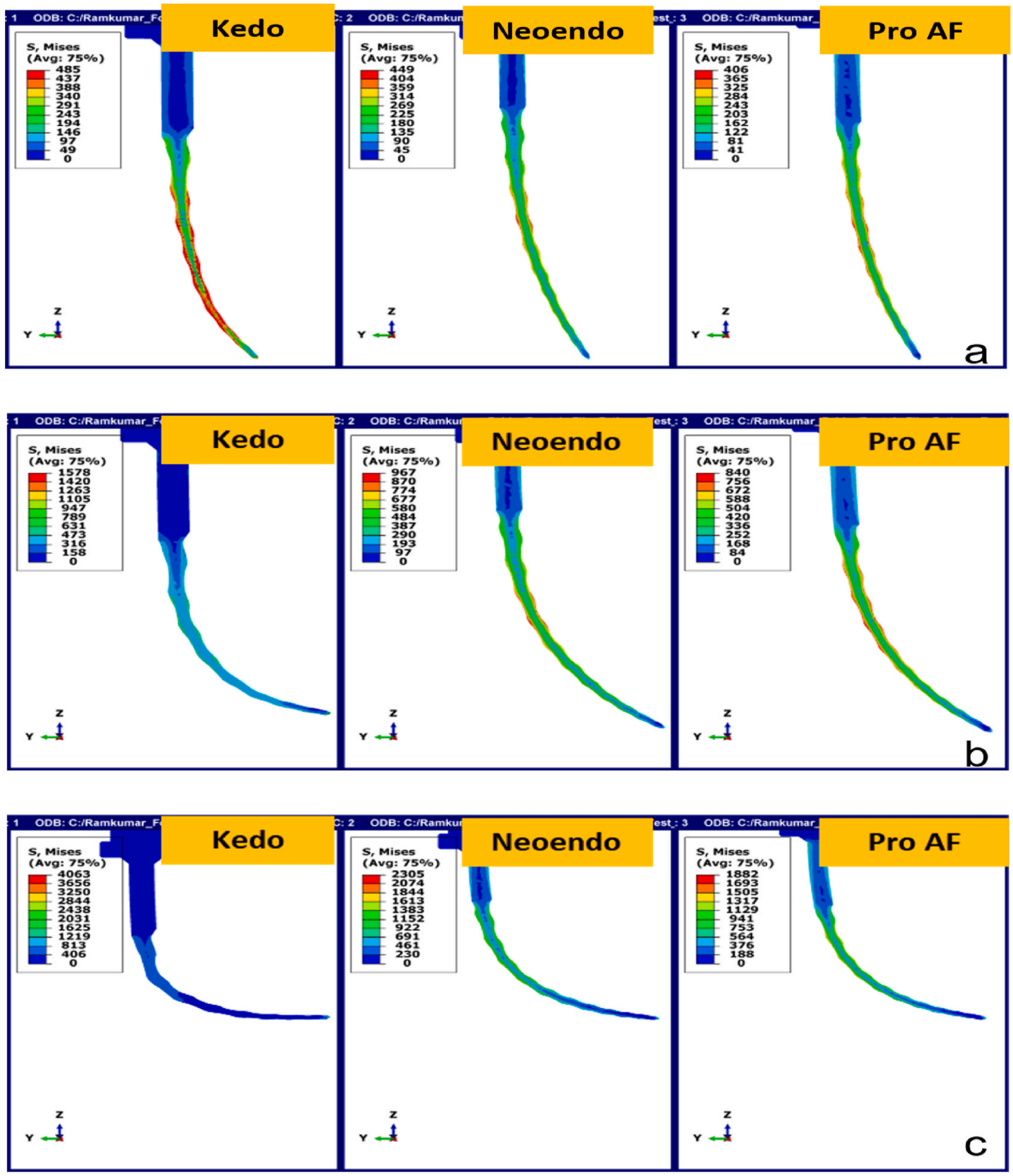

Fig. 6. Fatigue test – stress comparison at (a) 30 degree (a) 60 degree (a) 90 degree.

Table 4
Max Stress Value of Fatigue analysis.

S.No	Root canal angle (Degree)	Fatigue cycles		
		Kedo	Neoendo	Pro AF
1	30	5.909	9.647	13.25
2	60	2.675	4.301	6.496
3	90	1.023	1.697	2.004

mechanical properties than the conventional NiTi files, including improved flexibility, reduced susceptibility to cracking, and increased fracture toughness.[19]

The use of Pro AF, Neoendo, and Kedo rotary systems, specifically designed for pediatric considerations, has marked the latest revolution in pediatric endodontics. These systems are tailored for primary teeth, which feature thinner dentinal walls, curved canals, and smaller dimensions. Among these, Pro AF showcases superior resistance to fatigue and enhanced flexibility for use in complicated curvature cases. The results showed that Kedo files are highly effective in managing moderate canal curvatures; however, stress levels tend to increase with pronounced root curvatures. Meanwhile, Neoendo files showed an intermediate performance. The Goodman fatigue model was used to predict the fatigue life of these rotary files under cyclic loading. This approach establishes a correlation between cyclic stress and the NCF, providing a framework for evaluating instrument durability. Among the tested files, Pro AF showed the highest NCF values and strong resistance to simulation under clinical conditions. Simulation using different canal curvatures 30°, 60°, 90° revealed that higher curvatures significantly reduce fatigue life due to increased stress accumulation.

The literature highlights the critical role of heat-treated NiTi alloys in enhancing cyclic fatigue resistance, as heat treatment stabilizes the martensitic transformation phase, improving flexibility and minimizing fracture risk.[21,23]

The material and geometrical properties of the Pro AF, featuring a heat-treated NiTi alloy and triangular cross-section design, significantly

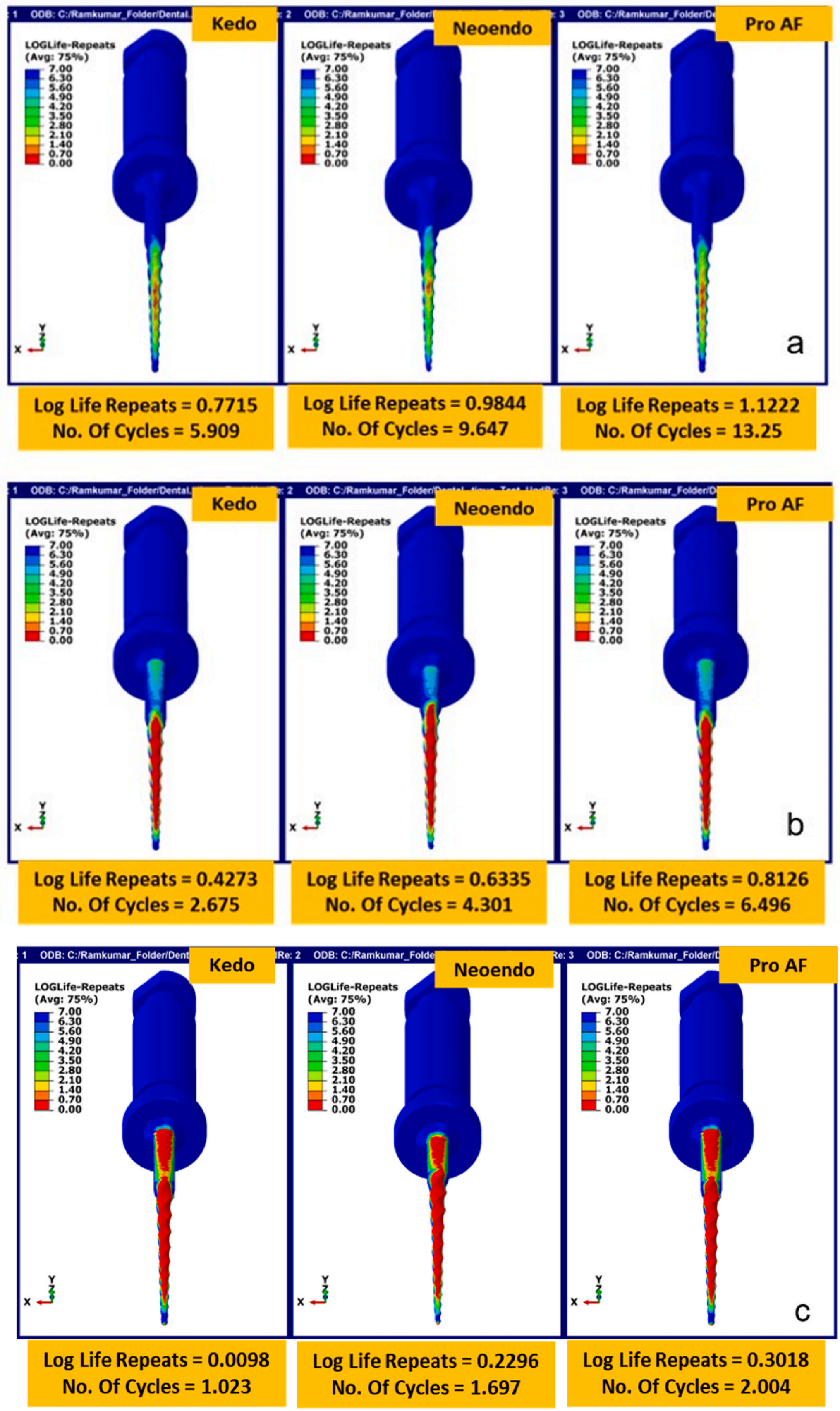

Fig. 7. Fatigue test – no. of cycles comparison at (a) 30 degree (b) 60 degree (c) 90 degree.

enhance its performance for primary teeth. These properties reduce stress concentrations and extend fatigue life, contributing to enhanced clinical safety. Finite element analysis (FEA) may play an important role in the future, but it does have some limitations. It requires careful consideration of numerous parameters, and validating experimental data is essential for ensuring accurate results. While FEA effectively models tooth anatomy and rotary file behavior, it does not account for factors such as canal length, diameter, and irregular shapes, which limits the broader applicability of its findings. The study's methodology demonstrates significant strengths by utilizing Finite Element Analysis (FEA) to evaluate cyclic fatigue resistance in pediatric rotary files with precision and control, eliminating operator variability. Advanced imaging techniques, such as nano-scanning and micro-CT, coupled with CAD modeling and meshing processes, ensure robust and reliable simulations. The application of Goodman's fatigue model and S-N curve analysis provides detailed insights into stress distribution and fatigue life across varying canal curvatures, replicating clinical scenarios effectively. Future research should focus on refining design parameters, validating findings in the clinical environment, and integrating patient-specific factors to optimize the use of rotary files in pediatric endodontics, ultimately enhancing procedural safety and outcomes for pediatric patients.

5. Conclusion

Using the Finite element analysis (FEA) the following conclusions have been obtained. Among the three pediatric rotary files evaluated the Pro AF Baby demonstrated better fatigue resistance and safety for endodontic procedures in primary molars with complex root canal curvatures. These findings emphasize the importance of material properties and file design to improve the clinical outcomes.

Ethical approval and informed consent statements

Ethical approval for this study was obtained from the university ethics committee (CSP-III/24/SEP/11/406).

Statements and declarations

Not Applicable.

Patients/guardian consent

Not Applicable as it is Finite Element Analysis Study.

Funding

Self-funded

Declaration of competing interest

The authors do not have any financial interest in the companies whose materials are included in this article.

Acknowledgements

We sincerely thank Mr. Ramkumar Murugan, CAE specialist, for helping us with the finite element model set up and analysis.

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