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Review

Finite Element Analysis of the Mechanical Behaviors of Endodontic Nickel–Titanium Rotary Files: A Review

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Abstract. An endodontic rotary file is a special instrument used in the treatment of dental pulp and surrounding tissues. They are available in a wide range of sizes and configurations, specifically tailored to accommodate the narrow and curved root canals of the teeth. Consequently, dental rotary files are slender, flexible, and generally made of a nickel-titanium alloy. The investigation of mechanical behaviors of dental files can be effectively conducted using computational approaches, such as the finite element method. This numerical tool is widely used in many engineering applications, especially for solid mechanics and structural problems. With the finite element method, the reliability and safety of dental files can be preliminarily assessed in a short period of time. This report reviews applications of the finite element analysis method to investigate the mechanical responses of endodontic rotary files. Both the finite element modeling of the files and applications of the method to rotary file problems are included in the study. This review includes the stress distribution, flexibility and stiffness, and fatigue life of the files. There have been a variety of approaches to model files under flexural and torsional loads. Static analysis with simple loading conditions was adopted in most of the studies. The analytical approach can be improved so that files under working conditions are accurately modelled. Moreover, there is a need for verification of the finite element solutions with experimental or clinical studies.

Keywords: Endodontic, nickel–titanium instrument, dental, finite element method, review literature.

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1. Introduction

Endodontics (root canal treatment) is one of the most predictable treatments in dentistry [1, 2]. A successful treatment outcome involves the ability to locate, clean, shape and seal the entire root canal system [3]. Disinfection of a root canal system involves many steps and the root canal treatment procedure includes changing the environment in the system considering the access opening, cleaning and shaping the canals with a chemo-mechanical root canal preparation, applying medications that have an antibacterial effect and filling the root canal with obturating material [4-6]. However, the most important step in root canal disinfection comes mainly from mechanical instrumentation with files [7, 8]. Files used in dentistry can be divided into two major groups; that is, hand operated files (hand file) and engine-driven files (rotary file). Both files are used to prepare root canals, but their fabrication procedures are completely different. A hand file involves twisting a wire, usually a stainless-steel wire, while a rotary file involves grinding a nickel–titanium (NiTi) alloy wire. The only exception is the Twisted (SybronEndo, Orange, CA, USA) file, which is a rotary file that is fabricated using the twisting method. Hand files have been used in root canal procedures since the beginning of endodontics. They have been used as a measuring tool for investigating the length of each root canal and their blade is used to cut the infected dentinal wall. Moreover, hand files can be used in many techniques to create a proper root canal shape to facilitate root canal irrigation and medication and root canal filling material delivery. However, root canal preparation with hand files can lead to many errors, which compromises the treatment outcomes of root canal treatment, especially in curved root canals [9]. Rotary files were invented to facilitate the root canal preparation procedure. They can shorten the time required for using instruments. Reducing the time a patient has to sit in the chair can also increase community acceptance of dental care [10]. A number of studies revealed the superior efficacy of rotary files over hand files [11-13]. However, hand files are still used as one of the essential instruments in endodontics. They are used to negotiate the canal path, measure the length and create a smooth reproducible path (Glidepath) as a gliding path before introducing rotary files into the root canals. Thus, the rotary files cannot be used solely without hand files; although, some manufacturers claimed that their file, the Reciproc (VDW, Munich, Germany), may not need a glidepath in most cases.

The main functions of a rotary file include shaping and cleaning the root canals by continuously or reciprocally rotating the file in the root canals, as shown in Fig. 1. The file is driven by an electric motor installed in the hand piece. The characteristics and developments of engine-driven endodontic rotary files in the past decades have been thoroughly summarized in review articles [14, 15] and a book chapter [16]. A typical characteristic of rotary files is presented in Fig. 2. The attachment section consists mainly of a shank that is connected to the hand piece. The working section includes a shaft or non-cutting part and the cutting part. Commercially available rotary files have a variety of cross-sectional shapes. The cutting portion of the files is usually designed with a taper. There are both constant- or fixed-taper files and variable-taper files. The physical parameters of the files include a cross-sectional shape, taper, radial land, grooves or flutes, helical angle and pitch, as shown in Fig. 3. Currently, a majority of engine-driven rotary files are fabricated from a nickel–titanium (NiTi) alloy because of its superior flexibility, superelasticity and fatigue resistance. NiTi alloys or nitinol contain 55% nickel and 45% titanium. The alloys can exist in two crystal phases, namely austenitic and martensitic phases. The phase transformation between austenite and martensite is achieved by applying heat or stress to the alloy [17]. Failures of rotary files in clinical incidence were related to proficiency of the operator and the number of uses of the instruments [18]. The modes of mechanical failure of the files include fracture failures due to excessive shear stress from the torsional load and flexural fatigue due to curved canals [19]. Torsional failure of rotary files was experimentally investigated in several studies [20-23]. Scanning electron microscopic images of the torsional fracture surfaces were presented. Similarly, rotary files have been tested under a flexural load to determine the fatigue life of the files [24-27].

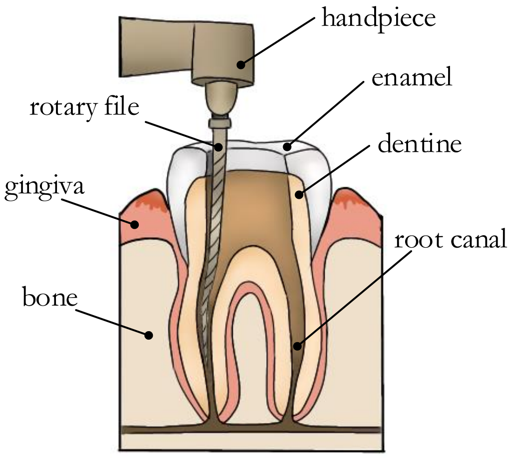

Fig. 1. A rotary file working in the root canal.

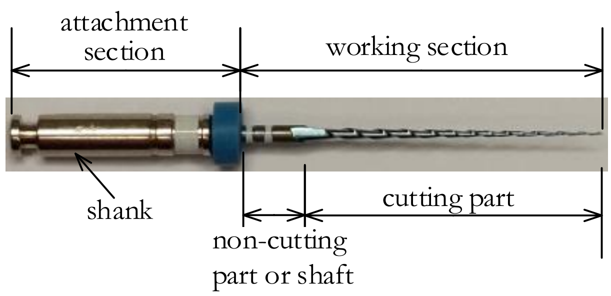

Fig. 2. An attachment section and a working section of the endodontic rotary file

In addition to experimental studies, the mechanical responses of endodontic rotary files were investigated using the finite element method. Finite element analysis (FEA) involves a numerical approach that is widely used in many engineering applications, ranging from mechanical, civil and electrical engineering to bioengineering. In solid mechanics and structural analysis, FEA has been applied to determine the mechanical behavior of solid structures. In addition to stress, strain and deformation of solid structures, more complicated behaviors such as vibration, fracture and fatigue can also be modelled using FEA. This method is less costly and takes less time compared to experimental investigations, *in vivo* studies, or clinical studies. It is also more convenient to perform FEA in a study with many variable parameters. However, it is important to have an accurate solid model of the problem, realistic boundaries and loading conditions and a correct interpretation of the simulation to achieve reliable solutions to the problems. The finite element method has been used as a numerical tool in the field of dentistry [28-31], including the fields of prosthodontics, restorative dentistry, implantology and orthodontics. The method has also been applied to the field of endodontics with analyzes of root canal instruments and dental files. While there are numerous review papers on rotary files in the existing literature, the examination of FEA of rotary files is limited to the critical review conducted by Chien *et al.* [32]. However, this study only covers the methodology of implementing FEA on rotary files, neglecting other crucial aspects related to the investigation of mechanical responses, including stress distribution, flexibility, and failure of the file. In this study, the application of FEA to investigate the mechanical behaviors of the NiTi endodontic rotary file was reviewed. The development and transformation of NiTi rotary files are briefly presented in the following section. The procedures used to create and analyze FEA models of rotary files are outlined in the next section. The section includes a solid model of rotary files, material modeling of the NiTi alloy and loading and boundary conditions used in the FEA. The following three sections summarize studies that applied FEA to determine the mechanical behaviors of the rotary files. The literature was reviewed according to a) stress in the files, b) flexibility and deformation and c) fatigue failure. The limitations and disadvantages of previous studies are discussed, along with future research and other opportunities, at the end of this report.

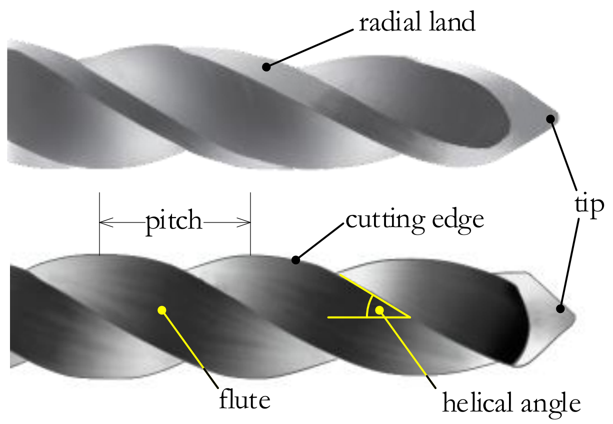

Fig. 3. The physical parameters of the endodontic rotary files.

2. Nickel–Titanium Instruments

Rotary files were first introduced in endodontics in the 1990s. They dramatically changed the way dentists shape root canals. However, as with any newly invented instrument, there were major drawbacks, including fracture resistance. It was found that the new instruments easily broke during operations. Theoretically, a rotary file should be more difficult to break than the hand file considering its produced material. However, rotary files included a rotary motor, which accelerated breakage according to dentists. Some dentists chose to not use these instruments due to the new learning curve they had to face and concern for instrument breakage [33-35].

Rotary files have been developed since their introduction in the 1990s. The various generations of rotary files were defined by different aspects. For ease of understanding in this review, the development of rotary files was divided into five generations according to the major changes in each generation, which were previously described by Dr. Ruddle [36].

After almost three decades of development, files can still break. The fracture characteristics of rotary files, which were first described in the dentistry literature in 2000 [37], were torsional fractures and cyclic fatigue fractures. The torsional fracture occurred when the tip or a part of the file was locked in the root canal, but the file continued to rotate. The torsional stress exceeded the limit of the file and then the fracture occurred. Thus, a torque-controlled motor was invented to reduce the chances of this fracture occurring. The motor allowed the clinician to set the proper torsional moment with each file according to the manufacturer's recommendations. If the motor sensed torque that could jeopardize the file, the motor automatically reversed the rotation to prevent excess torsional stress. However, torsional fracture could not be completely prevented because torsional stress can suddenly increase with improper apical force of the clinician. Furthermore, clinicians were encouraged to create a glidepath, as mentioned previously, in order to create a smooth path, which reduced the chance of the file locking in the canal. Second, cyclic fatigue fractures occurred when the file rotated in the curved canal. The fatigue accumulation was mostly found at the curvature from repetitive operations until the file was broken. Thus, the number of usages needed to be limited to prevent this type of breakage. Subsequently, a single-use protocol was encouraged for all rotary files. This could help reduce the chances of file breakage and also prevent prion cross-contamination that could not be eliminated by standard sterilization methods. However, the single-use protocol is still not practical, especially in third world countries where the economic status is poor. Even though there has been remarkable development of these files, files can still break even after first use [38]. A strategy to prevent this breakage is to invent a new novel NiTi alloy, which has been described as successful in the literature.

Dental rotary files fabricated with a nickel–titanium alloy have been used in root canal treatments. New

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instruments have been developed continuously and were improved in various aspects, including physical characteristics, materials and operations. Fracture strength and flexibility are among the desired mechanical behaviors due to the nature of the size and curvature of the root canal. Research in the field of rotary files in dental applications has included many variations. The finite element method is a numerical method that has been used to investigate the mechanical behavior of rotary files. FEA solutions help designers obtain estimated solutions quickly for design and testing processes. Modeling and analysis of rotary files using the finite element method are reviewed in the following section.

3. Finite Element Analysis

Although there have been more than a few research papers on the application of FEA to dental rotary files, there is no standard guideline for boundary or load conditions [32]. It has been agreed that rotary files are subjected to mainly bending and torsional loads during root canal operations. A bending load is generated when the file is bent or curved when inserted into a curved root canal. Torsional load is induced in the file because of the friction and resistant forces from the cutting operation on the canal wall. The torsional load can be remarkably high if the tip of the instrument is stuck in the canal wall while torque is still applied to the instrument. To obtain an accurate FEA solution, it is necessary to simulate both types of loads applied to the instrument. The accuracy of the FEA prediction is directly dependent on the precision of the modeling compared to real-world problems. Although there is mutual agreement on the type of load applied in practical applications, modeling of both bending and torsional loading conditions in the FEA model was different in each study.

Applications of the FEA method to investigate mechanical behaviors of endodontic rotary instruments can be categorized into three groups, which are stress in the instrument, stiffness of the instrument and fatigue behavior of the instrument. In the first group, the dental files were subjected to either a flexural load, a torsional load or both types of loading simultaneously. The stress generated in the files directly relates to failure of the instrument. The second focused on the stiffness of the instrument, which is defined by the ratio of deformation to the applied load. In this case, the stiffness of the instrument under a flexural load and torsional load was defined as the ratio of the deflection and angle of twist of the file per unit applied load. Finally, a handful of studies investigated the fatigue behavior of dental rotary files. Although fatigue is an important mechanical behavior and failure mode of dental files, studies that applied FEA to this type of problem are limited.

Research on dental files using the FEA method usually utilized commercial finite element packages. Ansys and Abaqus are two of the most wildly adopted FEA software programs in this field of study. The general procedure of FEA is shown in Fig. 4. Pre-processing or model preparation is the first step in FEA. It includes preparation of the solid model or geometric model of dental files, discretization or meshing of the model, defining the properties of the material and finally, applying load and boundary conditions. In the processing phase, the FEA software performs numerical analysis to solve the set of equations that govern the behavior of the elements. Then, the results obtained from the analysis are examined and presented in the post-processing step. The review in this section begins with the methodology used to develop FEA modeling; i.e. solid modeling of the specimens, material modeling and loading and boundary conditions. Three groups of studies described previously will be reviewed in the following sections.

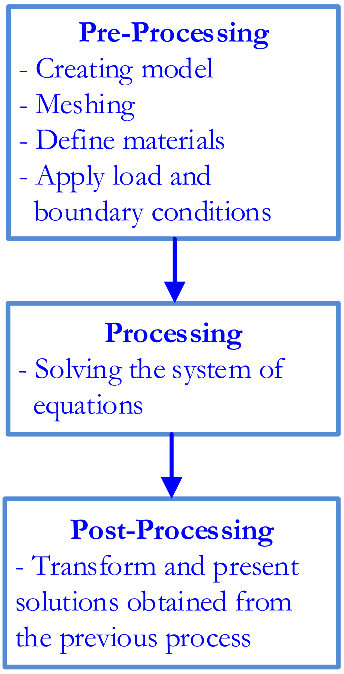


Fig. 4. The general procedure of finite element analysis.

3.1. Solid Model

The FEA method used in the field of stress analysis is a numerical simulation of the mechanical behaviors of solid structures. The structure of interest is discretized into finite solid elements or subdomains before numerically solving for mechanical behaviors, such as stress, strain and displacement. Domain discretization or meshing of the problem can be accomplished using FEA software or other specific software. Since the shapes of dental files are complicated and different from model to model, obtaining an accurate solid model of a dental file requires special attention and techniques. From the available literature on stress analysis in rotary files, shown in Table 1, the technique used to create a solid model of the rotary files can be categorized into four groups as follows.

3.1.1. Computer-generated model based on basic cross-sectional configurations

The first method used a basic cross-sectional configuration such as a triangle, rectangle, parallelogram, or other variants of these fundamental geometry structures as a primary cross-sectional pattern. Computeraided design (CAD) software is then used to generate a complete solid model of the instruments according to the specified cross-sectional size, length, taper and pitch. Basheer Ahamed *et al.* [39] used Pro/ENGINEER Wildfire 4.0 software (PTC Inc, Needham, MA) to create rotary instruments with a cross-sectional area of a triangle, convex triangle and triple U. Rotary files with a combination of all three cross sections were also included in the study. The WaveOne primary file with a tip size of ISO-25 and an apical taper of 8% was modelled in a study by El-Anwar *et al.* [40]. In that study, the original cross-sectional area of the convex triangle was simplified as a circular file with equivalent cross-sectional area. AutoDesk Inventor version 8.0 (Autodesk Inc., San Rafael, CA, USA) was utilized as CAD software. In addition to CAD software, mathematical software such as Matlab (MathWorks Inc., Natick, MA, USA) was also used to create a solid model of files for FEA. Roda-Casanova *et al.* [41] employed Matlab to create a dental file according to known parameters such as the diameter of the shaft, the diameter of the tip of the active part, the length of the active part, the total length of the file and the pitch of the active part. A rotary file with a squared cross-section was investigated in the study. A study by Galal and Hamdy [42] applied more complicated procedures to create solid models of NiTi rotary files using both SolidWorks and Matlab software. The 2D cross-sectional areas of a triangle, convex triangular, rectangle and parallelogram files were drawn using SolidWorks software and were then converted into the STereoLithography (STL) file format (.stl file). The .stl file was then imported into Matlab software and used with other design parameters such as pitch, taper and off-center cross sections to create a solid model for FEA.

3.1.2. Computer-generated model based on configurations of a commercial file

The second group of geometric models of the files was generated from file configurations of commercially available rotary files using procedures similar to those in the first category. The cross-sectional area of the instruments was modelled according to the information provided by the manufacturers or from the available literature. Similar to the first group, 3D-CAD software is required to complete the solid modeling of the files. Some complicated configurations may be neglected to make the modeling possible. A study by Xu and Zheng [43] modelled six rotary files based on commercially available instruments. They included the convex triangle (ProTaper), the triple helix (Hero 642), the S-type (Mtwo), the triple U (ProFile), the Z-type (Quantec) and the triangle (NiTiflex). The same taper of 0.04 mm and tip diameter of 0.4 mm were assumed in all models. The ProTaper and ProFile instruments with a convex triangle and triple U, respectively, were investigated by Berutti *et al.* [44]. The cross-sectional area of both models was assumed to be inscribed in a circle with a 4 mm diameter. The tapering of the files was neglected in that study. The pitch of the file was characterized by continuously rotating the cross-section through 360 degrees over an axial length of 1.8 mm. The RaCe file (FGK Dentaire, La-Chaux-de-Fonds, Switzerland) with a simple triangle cross-section was investigated in a study by Karamooz-Ravari and Dehghani [45]. It was assumed that the pitch and radius of the file were linearly varied along the length. Zhang *et al.* [46] modelled three types of rotary instruments (ProTaper, Hero 642 and NRT) based on the derived mathematical description of the radius, taper, pitch and relative angle for the orientation of the cross-section between two planes. Similarly, the ProTaper Universal F2 file was investigated in a study by Gao *et al.* [47]. CATIA software along with the geometric data of the file from the manufacturer and available data in the literature were adopted to create a 3D solid model of the file. A travelling optical microscope was also used to measure the pitch of the file. Comparable processes were used to generate 3D models of WaveOne, ProTaper F1 and GTX files by El-Anwar *et al.* [48]. The first two models were slightly different in their taper, which was ignored, and the same 3D model was adopted.

3.1.3. Computer-generated model based on measured images of an available file

Instead of using the data profile of the instrument from the literature, some studies obtained data with an image measuring device or a microscope before processing them using CAD software to obtain the FEA model. A study by Zhang *et al.* [49] used an image measuring device (VCAD-1010; HLEO, Beijing, China) to measure cross-sectional profiles of 10 different file models. The data obtained were then used in SolidWorks software to create a solid model of each instrument. Niño-Barrera *et al.* [50] measured the profile of the instruments at the widest and narrowest points on the longitudinal axis of the file using a profile projector with a resolution of 0.01 mm. Autodesk Inventor CAD software was used to generate the model according to the measured data. In a study by Montalvão and Alçada [51], ProFile GT 20/.06 and GT Series X 20/.06 dental files were measured using a Mitutoyo (Tokyo, Japan) PJ-A300 profile projector and a Leica (Wetzlar, Germany) Zoom 2000 microscope. In the same way, ProTaper Gold (Dentsply, Tulsa Dental Specialties, Tulsa, OK, USA) and ProTaper Universal (Dentsply Maillefer, Ballaigues, Switzerland) were inspected with a stereomicroscope at magnifications of ×5, ×10 and ×16 [52].

3.1.4. Micro-CT scanner

Micro-computed tomography (micro-CT) can be used to scan a sample with very high resolution. Kim *et al.* [53] and Kim *et al.* [54] used a micro-CT scanner to scan rotary files at an interval of 2 μm to obtain 2D images of the cross-sectional slices. A set of 2D slice images was then processed with 3D modeling software to reconstruct a 3D solid model for FEA. In both studies, IDEAS11 NX (UGS, Plano, TX, USA) was used as modeling software. Some modifications, such as data cleaning and noise reduction of the images from the micro-CT scanner, were required to acquire the best solid model. This method can be considered as a direct and thorough measurement of the file configuration, which is significantly different from other methods.

3.2. Material Modeling

In addition to creating a solid model, mechanical behavior in terms of the stress–strain relation of the nickel–titanium (NiTi) alloy is required for FEA. A NiTi alloy possesses unique mechanical properties such as a shape memory effect (SMA), superelasticity, temperature-dependent behavior and biocompatibility [55]. The typical stress–strain curve of the NiTi alloy showing loading and unloading behaviors is presented in Fig. 5. During loading, stress is linearly related to strain in the initial part where the alloy is in the austenite phase. Subsequently, the transformation from austenite to martensite begins and ends, which is represented by the transformation plateau on the stress–strain curve. The stress–strain diagram of the martensite phase behaves similarly to conventional materials, i.e., elastic and plastic strains are noticed. If the applied stress is increased, permanent or unrecoverable strain is observed, and the specimen is finally fractured. If the specimen is unloaded before permanent deformation occurs, the stress–strain relationship follows the unloading part, and the martensite phase is returned to its original austenite phase. With superelastic properties, the NiTi alloy exhibits non-linear elastic recovery during unloading, which is an important property for endodontic instruments. The mechanical behavior of the cyclic superelastic tests of the NiTi alloy was observed in a study by Chen *et al.* [56]. In addition to stress-induced phase transformation, phase transformation of a NiTi alloy can be controlled by changes in temperature. The stress and temperature-induced phase transformation of the alloy can be presented in a stress–strain–temperature diagram of the NiTi alloy [57-59]. For rotary files, a thermo-mechanical procedure was developed to improve the mechanical properties of a conventional alloy. This new type of NiTi alloy, after receiving a thermo-mechanical treatment, is called M-wire (Sportswire LLC, Langley, OK, USA). Typically, the mechanical properties in terms of tensile strength, flexibility, fatigue life and hardness of the M-wire are superior to those of the conventional alloy. Young's modulus of the new M-wire is also lower than that of the NiTi alloy, so it is more flexible under a combined load. The stress–strain diagram, including metallurgical characterization of the conventional NiTi alloy and M-wire, was investigated [60-62].

In the finite element investigation, the material of the instruments was modelled as a typical isotropic material or a superelastic material with a non-linear stress–strain diagram. Studies [41, 42, 46, 52, 63] treated the NiTi alloy as a typical isotropic material, and only the Young's modulus and Poisson ratio were the required material's parameters. Static structural analysis was usually adopted in this type of analysis, i.e., mechanical responses of the structure were determined for a given applied loading. Static analysis is straightforward and stress induced in the model is valid only in the linear range of a stress–strain diagram. The result of this approach can be used to compare stress induced in the instruments with different cross-sectional areas. However, stress and strain solutions may not be accurate if the applied load is high enough such that the material is in a transformation plateau or martensite phase. More realistic material modeling was performed in some studies [44, 53] in which the non-linear behavior of material was taken into account. Berutti *et al.* [44] represented stress–strain relationships with three straight lines: a linear line with a high slope in the austenitic phase, almost a flat line in the transformation phase and a linear line with a lower slope than the first part. Young's modulus of the NiTi alloy for each section was approximated at 35.7, 0.86 and 11.6 GPa, respectively. In addition to the approximation of the stress–strain diagram as a combination of three straight lines, several studies [39, 40, 43, 48, 49, 51, 54, 64] estimated the stress–strain relation of NiTi using a multi-linear curve. Xu and Zheng [43] and Montalvão and Alçada [51] applied the multi-kinematic hardening plastic material model in Ansys software to represent the stress–strain relation in FEA. However, most studies have been concerned with mechanical responses on the loading path. A study by Legrand *et al.* [64] not only considered the stress–strain relation in the unloading path, but tensile–compressive asymmetry was also included in the model. The stress–strain relationship in the loading and unloading paths of the model was comparable to that of the test data. In addition to non-linear modeling of material properties, a large deformation analysis was also required to obtain realistic mechanical response. A higher-order 3D 20-node solid element, called Solid 186 in Ansys software, was used in some studies [39, 40, 48], while a similar Solid 187 element was adopted in another study [51]. Both elements were capable of solving problems with plasticity, hyperelasticity, large deflection and large strain. In conclusion, materials of NiTi rotary instruments have been modelled in FEA ranging from a conventional isotropic material to a more complex non-linear elastic material with superelastic capability. The problem was also analyzed as a linear static problem or a non-linear problem with different modeling approaches. FEA with a large deformation option was also included.

3.3. Loading and Boundary Conditions

One of the most important processes in FEA is defining the loading and boundary conditions. Inappropriate modeling of these conditions will result in enormous discrepancies of the obtained solutions. Good boundary and load conditions are those that correspond well to the physical conditions of the problem. Under general working conditions, the instrument is subjected to both flexural and torsional loading. The flexural load is induced by the curved path of the root canal, such that the instrument is bent during insertion. The torsional load is a

Table 1. List of studies on stress analysis.

Studies	File Characteristic	Software/ Load	Significant Finding
Berutti *et al.* [44]	Constant cross-sectional area of ProTaper and ProFile	Ansys/ Bending and torsion	The ProTaper model is stronger but less elastic than the ProFile model. An ideal instrument should possess both elasticity and strength.
Xu *et al.* [43]	Commercial files: ProTaper, Hero642, Mtwo, ProFile, Quantec, and NiTiflex	Ansys/ Torsion	The maximum stress and stress distribution were influenced by the cross-sectional profile.
Kim *et al.* [53]	Commercial files: ProFile, HeroShaper, Mtwo and NRT	Abaqus/ Bending and torsion	Instruments with rectangular-based cross sections created higher stress differentials during simulated shaping of curved canals than instruments with triangle-based cross sections did.
Kim *et al.* [54]	Commercial files: ProFile, ProTaper and ProTaper Universal	Abaqus/ Bending and torsion	Adding a U-shaped groove to the convex triangular design decreases the flexural rigidity of the original ProTaper design. Under torsion, the maximum stress occurs at the bottom of the groove.
Zhang *et al.* [49]	10 files with different cross sections.	Ansys/ Bending and torsion	All files did not fail when they were bent up to 50°. On the contrary, the stresses induced in some models were higher than the ultimate strength of the material if a torsional load of greater than 1.0 N-mm was applied.
Niño-Barrera *et al.* [50]	Commercial files: Several series of Mtwo® files	Autodesk/ Bending and torsion	The von Mises stresses in the file models 10/0.04 and 25/0.06 were the highest in bending and torsion, respectively. It is recommended that both files should not be reused.
Basheer Ahamed *et al.* [39]	Single and combination of 3 cross-sectional designs	Ansys/ Torsion	A file with a combination of three cross-sectional designs showed the least bending stress.
Galal and Hamdy [42]	Triangle, convex triangular, parallelogram, and rectangle cross-sectional area	SolidWorks/ Bending and torsion	A specific geometrical design could be advantageous for either bending resistance or torsional resistance but not for both.
Montalvao and Alcada [51]	Commercial files: ProFile GT and ProFile GTX	Ansys/ Bending and torsion	The M-Wire file is more flexible and capable of stress relief than the conventional NiTi file.
El-Anwar *et al.* [48]	Commercial files: GTX, ProTaper and WaveOne	Ansys/ Bending and torsion	The M-Wire is marginally more resilient than the conventional NiTi file in regular operation. For severe locking conditions, both materials perform similarly.
Galal *et al.* [52]	Commercial files: Protaper Gold and Protaper Universal	SolidWorks/ Bending and torsion	Thermomechanical treatment improves failure resistance and flexibility of the files.
Prati *et al.* [63]	Commercial file: conventional alloy and heat-treated alloy	Ansys/ Bending and torsion	Mechanical responses of conventional and heat-treated alloy instruments affect stress distribution in sound and highly-mineralized dentine.

Table 1. List of studies on stress analysis. (Continued)

Studies	File Characteristic	Software/ Load	Significant Findings
El-Anwar *et al.* [40]	Simplified to be a circular cross section with equivalent area	Ansys/ Bending and torsion	Stainless steel 316L is not suitable for dental files, and the life of a reciprocating file is shorter due to a higher load applied at the blade tip.
Zhang *et al.* [46]	Commercial files: HERO, ProTaper, and NRT	Ansys/ Bending and torsion	The stresses developed in the files are higher for a file with smaller core diameters. For both torsion and bending loads, maximum stresses always appear at the border of the file's cross section.
Gao *et al.* [47] 2.14 (2011)	Commercial files: ProTaper F2	LS-Dyna/ Bending	The stress and strain induced on the file are influenced by the abruptness and degree of curvature, as well as the location of the curved section.
Karamooz-Ravari and Dehghani [45]	Commercial files: RaCe endodontic file	Abaqus/ Bending	Material asymmetry affects the maximum von Mises stress and the force displacement response of the file's tip.
Roda-Casanova *et al.* [41]	Squared cross-sectional area	Abaqus/ Bending and torsion	An automated and computerized procedure can be used to generate the file with varying parameters for finite element and stress analysis
Zanza *et al.* [65]	Triangle, rectangle, square, and hollow square	FEEPlus/ Torsion	The polar moment of inertia is the most important cross-sectional factor in determining the torsional resistance of the file.

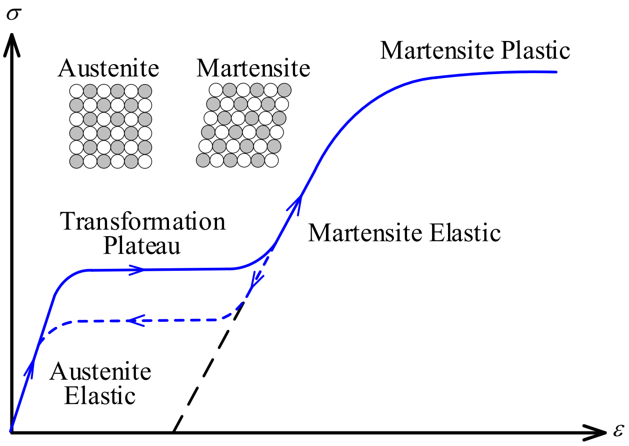


Fig. 5. Typical stress-strain relation of superelastic NiTi alloy [55].

result of the applied torque and resistive force between the rotary file and the wall of the root canal during dentine cutting. During normal operation, the magnitude of the torsional load is low compared with the magnitude of the flexural load. However, if the tip of the instrument is trapped or stuck on the wall of the root canal, while the applied torque is continuously applied, the magnitude of the torsional load could become exceptionally high, which can lead to torsional failure. Torsional failure can be avoided if the applied torque is terminated. Experienced dentists can easily avoid torsional failure of the instrument by disengaging the power before the file is trapped. On the other hand, bending stress on the instrument cannot be prevented, especially in acute curved canals. Since the rotary file is subjected to mainly two types of external load; i.e. bending and torsional loads, they are employed as load conditions in a FEA.

3.3.1. Bending Load

For an instrument subjected to bending or flexural load, the applied loading conditions in FEA have appeared in the literature in a variety of ways. Although there is a standard for endodontic instruments available in ISO 3630-1, as used in some studies [40, 48], many did not follow the standard. The loading conditions applied in FEAs are summarized in Table 2. To subject the rotary file to bending condition, either moment, force, or displacement can be applied to the specimen. A study by Zhang *et al.* [46] applied a pure bending moment of 1.0 N-mm to the simulated files. Berutti *et al.* [44] investigated the stress distribution in files of constant cross sections by securing one end and applying the bending moment to the other end of the files. Some studies applied force at the tip and clamped the shaft of the files. The magnitude of the applied force has varied from study to study. In several studies [42, 50-54], a force of 1.0 N was used, while the reaction force from a static analysis was used in a study by Zhang *et al.* [49]. A study by Niño-Barrera *et al.* [50] also utilized a more complex loading condition to obtain bending of the rotary files. In addition to a fixed support at the shaft and an applied force at the tip, the file was also fixed at 4 mm from the tip of the file. In some investigations [45, 51, 53, 54], displacement was enforced at the tip of the file to create a flexural loading condition. A deflection of 2 mm of the tip of the file was used in some studies [51, 53, 54]. A similar displacement control loading method was used in a study by Zhang *et al.* [49] in which the specimen was bent by controlling the tip displacement. However, the degree of curvature was used to indicate the bending condition rather than linear displacement. The last group of bending configurations was based on the ISO 3630-1 international standard [40, 48]. According to the standard, the rotary file was fixed at 3 mm from the tip and a point load was applied to the end of the shaft until a 45° inclination was observed. In most of the studies, the bending load was applied by applying force or displacement to the specimens. A study by Gao *et al.* [47] utilized a more realistic method; i.e. using two straight tubes that constrained the file to a designated curvature. The curvature of the file could be adjusted by changing the location of the tubes. It was observed that different methods have been utilized to apply a bending load to the instrument. There is no unified approach that is widely accepted and adopted in studies using FEA.

3.3.2. Torsional Load

As with the bending load, several approaches have been used to simulate the torsional load on rotary instruments. The loading configurations for rotary instruments subjected to a torsional load are summarized in Table 3. Most of the loading configurations have consisted of fixing the file at a cross-section and applying torque at another cross-section. Studies by Xu and Zheng [43] and Niño-Barrera *et al.* [50] applied a torsional load to samples by fixing the tip of the file and applying torque at the other end. A torque of 2.5 N-mm was used in a study by Xu and Zheng [43], while the torques recommended by the manufacturers were employed for each file in a study by Niño-Barrera *et al.* [50]. The next category of loading configuration was similar to the first category, except for the fact that the models were fixed at a cross-section 4 mm from their tip [42, 51-54]. The same torque of 2.5 N-mm was applied to the shaft of the files. In addition to applying the load, some studies [51, 53, 54] also included angular displacement in their FEA. A twisting angle of 10° was enforced on the shaft of the instrument. Roda-Casanova *et al.* [41] used a slightly different approach to constrain the specimen; that is, clamping at 3 mm from the tip of the file. A torsional moment of 0.3 N-cm was applied at the other end. The other approach was to fix the shaft and apply a torsional load at the tip of the instrument [49]. In that study, torsional moments ranging from 0.25 to 2.0 N-mm were used so that the failure stress of the file was observed. The last category followed the ISO 3630-1 international standard [40, 48]. According to the standard, the model was fixed at 3 mm from the tip and loaded with a torsional moment of 0.3 N-cm at the file shaft. Similar to the bending load, several loading configurations for a torsional load can be found in the literature. Most of the cases are simulations of real-life conditions, which can be more complicated than a simulated case. Therefore, the results from a finite element simulation may be accurate for comparative studies only; i.e., FEA is accurate when determining whether a file is stronger than another file in general conditions. However, FEA may not be as accurate when used to determine the absolute strength of the file because of the complicated boundary and loading conditions in real-life situations.

The application of FEA to investigate the mechanical behaviors of dental rotary files can be categorized into three groups. They are stress in the files, flexibility and stiffness and fatigue failure. Research in each category is reviewed in the next three sections, respectively.

Table 2. Loading configurations for specimens subjected to bending load.

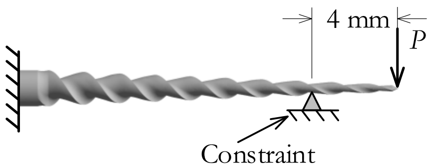
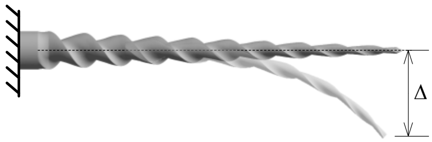
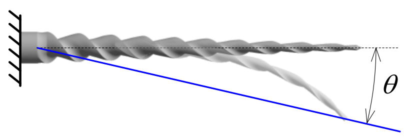
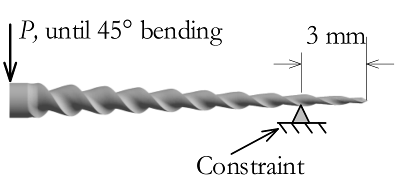
Categories	Loading configurations
1. Apply moment [44, 46]	
2. Apply force at the tip [42, 50-54]	
3. Apply force at the tip, fix at 4 mm from the tip. [50]	
4. Apply disp. at the tip [45, 51, 53, 54]	
5. Appy curvature [49]	
6. ISO 3630-1 [40, 48]	

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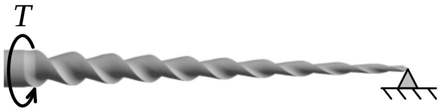
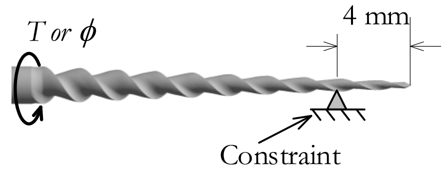
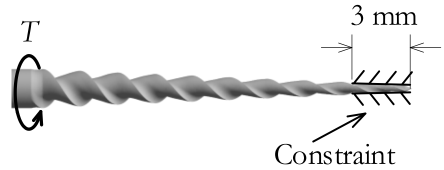
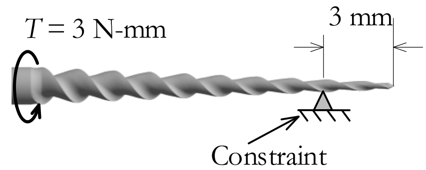
Table 3. Loading configurations for specimens subjected to torsional load.

Categories	Loading configurations
1. Fix the tip and apply torque at the shaft [43, 50]	
2. Fix at 4 mm from the tip and apply torque or rotation at the shaft [42, 51-54]	
3. Fix the last 3 mm from the tip and apply torque at the shaft [41]	
4. Fix the shaft and apply torque at the tip of the file [49]	
5. ISO 3630-1 [40, 48]	

4. Stress in the Rotary Files

Most studies on the mechanical behavior of an endodontic rotary instrument using FEA involved stress analysis of the instrument during root canal treatment. In addition to the stress distribution in the instruments, strain and deformation can also be determined. Most of the studies were concerned with the stress distribution and failures induced by stresses in the instruments. Usually, the distribution of von Mises stress in the files was determined for the specimen as it was subjected to bending or a torsional load. Then, the maximum von Mises stress was compared with the strength of the material, such as the yield stress, to determine whether the specimen failed. Alternatively, some studies aimed to compare the strength of the files with different geometries or materials. In this case, the maximum von Mises stress induced in the files was compared with other files. The model with the lowest maximum von Mises stress was considered as the strongest model; i.e., less likely to fail when subjected to the same load conditions. The von Mises stress at a point on the files can be determined from:

$$\sigma_v = \sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_3)^2\right]}, \qquad (1)$$

where, σ_i are principal stresses at the point.

The first set of studies investigated the distribution of stress in commercially available or theoretical cross-sectional dental files [41-44, 46, 48-50, 54]. Berutti *et al.* [44] compared stresses generated in the instruments and the elastic property of the mathematical models of the ProTaper and ProFile files under torsional and bending moments. They concluded that the ProFile model was more flexible than the ProTaper model, but the stress generated in the ProTaper model was lower than the other. Thus, the ProTaper model was stronger than the ProFile model. Kim *et al.* [54] expanded the study by Berutti *et al.* [44] by adding a ProTaper Universal to their study. The stress distributions of three rotary file models were determined. Similar to the previous study, ProFile had the highest flexibility, followed by ProTaper Universal and ProTaper, respectively. The flexural rigidity of the ProTaper can be lowered, thus increasing the flexibility, by adding a U-shaped groove in the middle of the convex triangular. In a study by Xu and Zheng [43], six commercial rotary files subjected to torsional loading were numerically investigated for stress distributions. The lowest stress levels were observed on ProTaper and Hero642, while the NiTiflex model generated the highest stress level compared with the other five models. The stress distribution was also found to be affected by the cross-sectional profile of the files, such as the inertia of the cross-sectional, depth of the flute, area of the inner core, radial land and peripheral surface ground. In another study, the stress distribution was determined for a Mtwo basic file series [50]. Von Mises stresses were found to be highest in file models 10/0.04 and 25/0.06 for bending and torsional loading, respectively. The geometrical design and material effects were investigated in a study by El-Anwar *et al.* [48]. The ProTaper and WaveOne files, which are fabricated from conventional NiTi and M-wire, respectively, have very similar geometries and were assumed to be identical geometrically in that study. The effect of a cross-sectional design was also studied by comparing the WaveOne file with the GTX file, which was also made from M-wire, but had a different cross-sectional design. The study showed that M-wire performed marginally better than the conventional NiTi in terms of resistance to stress failure, while a file with a larger cross-sectional area could withstand higher stresses. Zhang *et al.* [49] determined the stress distribution in dental files with 10 cross-sectional designs. They were square, triangular, U-type, large S-type, small S-type, convex triangle and four commercial files, which were Mani NRT, RT2, Quantec and Mtwo. It was found that all files in the study did not fail due to the bending load. In contrast, some models failed due to excessive stress when the applied torque was greater than 1.0 N-mm. The stress distribution in dental files was more influenced by the cross-sectional configuration of the file than other parameters, such as size and degree of tapering. In addition to studies on commercial files, rotary files with theoretical cross-sectional configurations were also investigated using FEA. Galal and Hamdy [42] investigated the stress distribution in dental files with different cross-sectional configurations, pitches, tapering and centering of the cross-section. Only theoretical cross-sectional areas of simple geometric configurations were included in this study. It was found that, to optimize the stress distribution for bending loads, a rectangular cross-sectional file with lower pitch, smaller taper and centered cross-section was preferred. If torsional resistance was desired, an instrument with a parallelogram cross-sectional configuration, lower pitch, higher taper and eccentric cross-section was favored. Zanza *et al.* [65] applied FEA to determine the maximum von Mises stress in rotary files subjected to a torsional load. The relationship of file parameters, such as the polar moment of inertia, the cross-sectional area, the inner core radius and the mass per volume on the maximum torsional load at failure, was determined. Linear regression analysis was performed to determine the relationship between the geometries of the files and the maximum torsional load at failure. The polar moment of inertia, not the mass or the cross-sectional area, was found to be the most significant cross-sectional property of the stress generated in the file. There was an attempt to determine the analytical solution for the stress distribution in rotary files subjected to torsional and bending loads in a study by Zhang *et al.* [46]. The derived formulas described the influence of geometric parameters (cross-sectional area, taper, helical angle and pitch) on the mechanical behavior of the instrument. FEA was employed to verify the analytical results. Although the obtained analytical solutions were not closed-form solutions for the files of interest, the mechanical behaviors of the instruments could be projected if one of the geometrical parameters was varied. Roda-Casanova *et al.* [41] proposed an automated procedure to create accurate geometrical structures of dental rotary files and analyzed them for maximum von Mises stresses of the files under bending and torsional loading. The automated procedure allowed designers to investigate the effect of file geometries on their mechanical responses very conveniently.

The second set of studies aimed to investigate the properties of the material that influenced the mechanical behavior of the files. El-Anwar *et al.* [40] compared the performance of files made of a nickel–titanium alloy and stainless steel 316L with an equivalent circular cross-sectional area. It was found that stainless steel was not suitable for either rotary or reciprocating files since the stress generated in the file was higher than the fracture stress. When compared to rotary instruments, the advantages of reciprocating files included lower torsional stress that was induced in the instruments, longer fatigue life and higher applied load on the root canal. However, a disadvantage of the reciprocating file is a shorter lifecycle caused by an intensified load applied at the tip of the blade. Currently, most commercial rotary files are made from the NiTi alloy. The mechanical properties of NiTi can be further improved by thermo-mechanical treatment. The impact of thermo-mechanical treatment of NiTi on mechanical responses under bending and torsion loads was examined by Montalvão and Alçada [51]. The ProFile GT (GT) and a GT Series X (GTX), which have similar geometries but are made from different materials, were investigated. GTX was made from M-wire, a NiTi alloy with thermo-mechanical treatment, while the other file was made from a conventional alloy, which was not heat-treated. Different stress–strain diagrams were employed in both finite element models. It was found that the thermo-mechanical process improved both flexural and torsional resistances; i.e. the maximum stress induced in the GTX model was lower than that of the GT model. For the GTX model, the deflection under the same flexural load was higher than that of the GT model, so the heat treatment process also improved the flexibility of the instrument. Similar conclusions were confirmed in a study by Galal *et al.* [52] in which ProTaper Universal with conventional alloy and ProTaper Gold with a heat-treated alloy were examined under bending and torsional loadings. A more complicated issue of material asymmetry under tensile and compressive loads was explored in a study by Karamooz-Ravari and Dehghani [45]. The flexural behavior of a RaCa file was simulated using the FEA method. The stress–strain relationship or a constitutive model of the NiTi alloy was modelled as a symmetrical model with tensile material behavior (SMT), symmetrical model with compressive material behavior (SMC) and asymmetrical material behavior (AM). It was discovered that the von Mises stress in the AM model was higher than that of the other two models. For force–displacement behavior, the behavior of SMC and AM models was practically similar. Thus, material asymmetry may have a considerable effect on the mechanical behavior of the rotary files.

All studies in the previous two categories simulated the loading conditions on the specimen by applying a flexural load or torsional moment to the specimens. These loading conditions are somewhat different from real-world situations, where the files are guided by the root canal. If a better simulation of the mechanical behaviors is preferred, a more realistic loading condition is required. Some studies proposed other techniques to better simulate loading conditions. Gao *et al.* [47] proposed to use two straight rigid tubes of various lengths to guide the file at the coronal and apical portions. Both tubes were located at different distances and orientated at various angles to create various curved portions of the instrument with different positions and degrees of curvature. The stress and strain induced in the files were directly influenced by the curvature configurations of the files. Kim *et al.* [53] employed a more realistic approach with a simulated rigid curved canal to guide the inserted file. The curved canal was created in a finite element program using plate elements. With the proposed loading approach, some mechanical behaviors, such as residual stresses, plastic strain and plastic deformation, could be captured after the file was withdrawn from the canal. A study by Necchi *et al.* [66] also utilized the simulated rigid curved canal. The stresses in the files during insertion and removal were determined. In addition, the study also simulated torsional stress if the tip of the file was locked in the canal wall. Another outstanding and more realistic technique to model the loading conditions on the rotary files was proposed in a study by Legrand *et al.* [64]. In that study, the root canal models were obtained from anatomical shapes of real root canals. Micro-CT was used to scan the human first maxillary molar. The obtained image was then processed to separate the root canal from other parts. A FEA model of the canal was then generated from the scanned endodontic anatomy. A recent study [67] utilized explicit non-linear dynamic analysis to capture the deformation, equivalent elastic strain and equivalent stress of the file during root canal operations. Explicit dynamic analysis is suitable for a highly transient phenomena. Theoretically, this analysis approach is more suitable for the problem than static analysis, if mechanical behaviors of the file during an operation in the root canal are preferred. However, explicit dynamic analysis requires more computational resources than static analysis.

Most of the finite element investigations on stress in rotary files were modelled by applying simplified loads to the files; for example, a torsional moment or a transverse point load, as shown in Table 1. Very few studies have attempted to simulate real-world loading conditions. Stress induced in the files due to flexural and torsional loads was used to determine the strength and failure of the files. The strength of rotary files depended on their physical characteristics, such as their cross-sectional profile, helical angle, taper and mechanical properties of the materials, which can be modified by heat treatment processes. The stress in rotary files is a fundamental parameter that can be determined by FEA. It can be used as a preliminary parameter to compare the strength of two rotary files.

5. Flexibility and Stiffness

In addition to stress analysis, FEA has been utilized to investigate mechanical responses, such as flexibility or stiffness, of rotary files. Both parameters refer to the ability to deform or the ability to remain in the original configuration. Flexibility and stiffness are inverse properties of each other. If an instrument is flexible or has high flexibility, its stiffness will be low and easily deformed when it is subjected to an applied load. Similar to stress and strain, flexibility and stiffness are crucial parameters for design consideration and failure analysis of rotary files. A suitable flexural flexibility of the rotary files is desired so that they can be easily inserted and bent into the curved canal. On the other hand, the flexural and rotational stiffness of the files is also required so that the cutting efficiency of the rotary file is achieved. Flexibility is generally determined by the ratio of deformation to the applied load. A flexible instrument is one that easily deforms or has a high ratio of deformation to the applied load. On the contrary, the workpiece has high stiffness if the workpiece has to be subjected to a high load to achieve a certain amount of deformation.

Several studies have used the FEA method to determine the flexibility or stiffness of dental rotary files. Table 4 summarizes studies on the flexibility and stiffness of dental files using the FEA method. Most of the studies simulated the rotary files under flexural and torsional loading by applying constraint at one end (or in a cross-section near one end or a portion of file at one end) and applying load or displacement at the other end, as shown in Tables 2 and 3. For flexural loading, the free end can be loaded with a specified transverse force, a particular displacement, or loading until there is a 45° inclination from the axis. For the case of loading with a specific force or load control, rotary files with different stiffnesses do not deform equally. On the other hand, for a test with displacement control, the rotary files would deform similarly, but the applied force would not be equal for files with different stiffness. Compared with the curved canal, displacement control seems to better replicate the real-world situation, since the canal configurations are fixed. In the case of torsional loading, the torsional moment was applied to a specified magnitude or until a specified angle of rotation was reached. Flexibility or stiffness was usually determined from the plots of applied load vs. deformation.

5.1. Effect of Heat Treatment

Most of the studies shown in Table 4 investigated the effects of the material and geometry of the files on the flexibility and stiffness of rotary files. The first category is a group of studies that investigated the effect of heat treatment on the flexibility of the files. Conventional NiTi has been adopted for use in the field of endodontics for decades because of its superelastic behavior and resistance to cyclic fatigue. The alloy was further improved with thermo-mechanical treatments to obtain desirable mechanical behaviors in terms of fracture strength, fatigue resistance and flexibility. Several types of heat-treated NiTi alloy have been utilized commercially [58]. They include controlled memory wire (CM wire), R-phase, M-wire, Max-wire, T-wire and C-wire. These heat-treated alloys have been shown to perform better in terms of flexibility and fatigue resistance [68, 69]. Santos *et al.* [70] demonstrated that rotary files made from CM NiTi have a higher flexibility than that of conventional NiTi files. A plot of bending moment vs. angle of inclination was used to determine flexural flexibility, while a plot of twist angle vs. torque was used to determine torsional stiffness. The fatigue resistance of the heat-treated instruments was shown to be superior. Stainless steel files were also included in the study and found to be less flexible compared with conventional and CM NiTi alloys. However, under torsional load, CM files exhibited the highest stress and deformation compared with conventional NiTi and stainless steel files. Therefore, the torsional stiffness of CM files was the lowest compared with other files. However, the authors claimed that the strain capacity of the CM alloy was three times higher than that of the other two materials, which can compensate for the low torsional stiffness of the CM file. A similar study by Montalvão *et al.* [71] compared the flexibility of M-wire and conventional NiTi files. Two models of rotary files with geometrical similarity but different materials; i.e. a ProFile GT (conventional alloy) and Profile GTX (M-wire alloy), were employed in the study. The finite element study showed that the Profile GTX was more flexible than the ProFile GT under bending. Stress induced under a flexural load of 1 N in the Profile GTX was also lower than that of the ProFile GT. Under torsional load, the M-wire file was also more flexible than the conventional file; i.e., angle of twist of the M-wire file was higher than that of the conventional file. X-ray diffraction and differential scanning calorimetry were used to analyze the phase transformation in both files and found that the GTX file contained R-phase at around 40°C, which is approximately body temperature. On the other hand, R-phase appeared in the GT file in the temperature range of around 10°C. Therefore, the M-wire file was more flexible than the rotary file with a conventional alloy, which agreed very well with the FEA results. Santos *et al.* [72] utilized similar approaches; i.e. FEA, X-ray diffraction and differential scanning calorimetry to investigate the flexibility of rotary files with alloys containing R-phase in their microstructure. FEA was performed with material properties from tensile tests of three types of NiTi alloys, which were austenite NiTi, austenite + R-phase NiTi and fully R-phased NiTi. Similar to the previous study, the rotary files with R-phase alloy showed higher flexibility compared with those of the other two alloys. The flexibility of M-wire and conventional NiTi rotary files was investigated using FEA and validated with *in vitro* tests in a study by Bonessio *et al.* [73]. Only torsional loading was included in the study and the results of FEA were in agreement with the *in vitro* study. The FEA results suggested that the flexibility of M-wire before initiating the transformation point can prevent premature failure of the files due to an accidentally excessive bending load. Martins *et al.* [74] investigated the flexibility and stiffness of the files under flexural and torsional loading of conventional and heat-treated alloys. The heat-treated alloys were modelled as alloys with heat treatment processes at 350°C and 450°C. Lower temperature heat treatment resulted in recovered superelastic austenite with rearranged dislocations, while the alloy with 450°C heat treatment had a R-phase structure. Rotary files with R-phase exhibited higher flexibility and lower stress levels. In conclusion, heat-treated NiTi alloys exhibited higher flexural flexibility, which was a positive consequence for a file used on curved root canals. However, the torsional stiffness of the instrument was decreased due to the heat treatment process. This could be a negative effect on the twist angle and cutting efficiency [75] of the files.

5.2. Effect of Geometry

In addition to the effects of the material properties, geometric configurations of the rotary files also influenced the flexibility and stiffness of the rotary files. Geometric configurations considered in the literature include cross-sectional geometries, taper, pitch, helix angle and flute length. The objectives of research using FEA in this category have varied from simple determination of the flexibility of commercial files to investigating the effects of each geometric parameter on the flexibility of files. Arbab-Chirani *et al.* [76] investigated the flexibility of five commercial NiTi rotary files with different cross-sectional configurations. All models had an equivalent tip diameter with various designs for tapers, pitch and cutting blades. The models of the rotary files with the most flexural and torsional flexibilities in descending order were Mtwo, ProFile, Hero, Hero Shaper and ProTaper, respectively. The flexibility in both bending and torsional loadings was similar. He and Ni [77] conducted a similar study on a commercial instrument model in which FEA was employed to improve the design of the V-Taper file. The influence of the helix angle, taper and flute length on flexibility of the V-Taper file under bending and torsional loads were investigated. Torsional stiffness and bending flexibility were optimized in the design improvement process. The impact of pitch or number of threads on the flexibility and stiffness of dental files was also studied. The effect of pitch under a torsional load [78] and bending load [79] was determined by the same group of researchers. The influence of the cross-sectional area was also included in both studies. It was found that designing files with a lower pitch and a larger cross-sectional area could improve the torsional rigidity of rotary instruments. Flexural loading was assessed in another study [79] and flexural stiffness and stresses induced in the file increased as pitch increased. This study also suggested that flexural stiffness and stress were associated with the center core area of the cross-section more than the cross-sectional area. Another file's parameter that influenced the file flexibility was the eccentricity of the cross-sectional area. There are two studies [80, 81] that specifically investigated the effect of an off-centered cross-section design on the flexibility of the instruments using FEA. Both studies found that the flexural flexibility of the off-centered rotary file was lower than that of the concentric file. However, the stress in the eccentric files was distributed in a pattern such that the maximum stress on the eccentric files was lower than that on the centered rotary file. Therefore, the off-centered cross-sectional design improved the strength of the file due to redistribution of the stress pattern. In terms of torsional behavior, the off-centered design did not improve the torsional stiffness. Part of the study by Martins *et al.* [74] also compared the flexibility of eccentric and concentric files and determined that the geometric eccentricity of the cross-sectional design increased the flexural flexibility of the files. This conclusion contradicted the first two studies; however, it was observed that, unlike the first two studies, the cross-sectional design and area of the two models used in this study [74] were not equivalent. Therefore, FEA results about the flexibility of files may not accurately reflect the effects of file eccentricity. While most studies improved flexural flexibility and torsional stiffness by modifying the cutting part of the files, a study by Kim *et al.* [82] proposed the modification of the shaft portions to improve their mechanical responses. The FEA simulation demonstrated that machining a spring into the shaft portion of the files significantly improved their flexural flexibility and torsional resistance. Therefore, the endurance of dental rotary files may be improved by adding a spring component to the shaft of the instruments.

5.3. Comparisons with *In Vitro* Studies

It is well accepted that to obtain accurate simulations of the mechanical behaviors of the file, several processes in the simulation such as geometric and material modeling, boundary and load conditions and interpretation of the results must be defined and performed accurately. Only one inappropriate modeling or selection may lead to erroneous simulation results. Therefore, the finite element method is usually verified with results from *in vitro* studies. There are a limited number of studies that utilized the experimental results to verify finite element solutions. A part of the study by Bonessio *et al.* [73] utilized a torsional test to verify the FEA study. Plots of applied torque vs. twist angles from the FEA were in good agreement with the experimental results. Another study [83] concentrated on comparing the FEA results with the experimental results. Three commercial files; i.e., Mtwo, RaCe and PTU F1, were included in the study. The bending flexibility and torsional stiffness were experimentally determined from the plots of moment vs. angle of inclination and the plots of torque vs. angle of twist. They were also compared with numerical solutions from an FEA. It was noticed that the solutions from both approaches agreed very well. Solutions from finite element solutions were also shown to be very well correlated with the experimental results for NiTi wire, spreader and NiTi rotary files [84]. From these validations, numerical solutions from FEA can be utilized to estimate the mechanical behaviors of the dental rotary files. In addition to using experimental solutions to verify the FEA method, FEA was also employed to verify analytical solutions [85]. An analytical solution was derived on the basis of Euler–Bernoulli equations and non-linear displacements. The RaCe and Mani NRT instruments were included in the study. The load–deflection curves of the rotary files under bending load from analytical solutions matched very well with the finite element solutions.

In conclusion, flexibility or stiffness is another crucial mechanical parameter of the rotary files. Both parameters are the inverse of each other and have both positive and negative effects on the files. Files with high flexibility or low stiffness can be easily bent and moved into a curved canal. On the other hand, files with high stiffness or low flexibility have better cutting performance. It is important, therefore, for a file to have suitable flexibility or stiffness, so that it can operate in the root canal with sufficient efficacy. Both parameters can be numerically determined using FEA. It is very helpful for a designer to virtually estimate the flexibility of a file without fabricating the file.

6. Fatigue failure

In addition to torsional overload, flexural fatigue is the most prominent failure mechanism in rotary files due to its small dimension and severe deformation. When a file rotates within a curved root canal, alternating compressive and tensile stresses can arise at any point of the file, leading to a failure mechanism known as flexural fatigue. A rotary file may experience fatigue failure even when subjected to stresses that are much lower than the yield stress of the material. Although the causes of fatigue failure in dental rotary files are well-recognized, studies looking at fatigue life using FEA are limited, unlike other fatigue problems in engineering applications. Only a handful of studies have applied the FEA method to predict the fatigue life or number of cycles to failure (NCF) of a rotary file. On the contrary, studies using an experimental approach to determine the NCF of dental files [24, 26, 86-90] can easily be found in the literature.

6.1. Stress Distribution Related to Fatigue Life

Martins *et al.* [91] employed the FEA method to investigate the influence of cyclic load on the flexural behavior of conventional NiTi and R-phase files. The mechanical properties of the cycled and uncycled samples were determined from the tests and used in the FEA to determine the mechanical responses of the rotary files. Cyclic loading was found to reduce stress levels and bending moments in conventional austenitic NiTi. On the other hand, the R-phase alloy demonstrated more consistent mechanical behaviors before and after exposure to fatigue loading. A study by Lee *et al.* [92] aimed to relate the stress distribution in a rotary file to the fatigue life of the file. FEA was utilized to obtain the stress distribution in the files subjected to flexural load when inserted into simulated root canals with 25°, 35° and 45° curvature. The maximum stress and location of the maximum stress from the FEA simulations were compared with the fatigue life and the location of failure of the file from the cyclic fatigue tests. The study observed that the maximum stress in the rotary file from finite element was related to fatigue failure of the instrument. The locations of the maximum stress from the FEA also corresponded to the failure location from the fatigue tests. Although this study did not determine the fatigue life of the instrument according to fatigue failure theory, stress analysis from FEA was used to predict the fatigue behavior of the files.

Table 4. List of studies on flexibility and stiffness.

Studies	File Characteristic	Software/ Load	Significant Findings
Santos *et al.* [70]	Commercial files: HyFlex with various materials	Abaqus/ Bending and torsion	CM files are more flexible and have greater potential fatigue resistance than conventional NiTi files.
Montalvao *et al.* [71]	Commercial files: ProFile GT and ProFile GTX	Ansys/ Bending and torsion	M-Wire NiTi increases the instrument's flexibility, and slight modifications of the file's geometry do not significantly change its mechanical responses.
Santos *et al.* [72]	Commercial files: ProTaper Universal F1	Abaqus/ Bending and torsion	R-phase files typically show higher flexibility but decreased torsional stiffness.
Bonessio *et al.* [73]	Commercial files: WaveOne	Abaqus/ Torsion	M-Wire instruments benefit from higher flexibility compared to conventional NiTi material.
Martins *et al.* [74]	Commercial files: ProTaper Next X1 and ProTaper Universal S2	Abaqus/ Bending and torsion	The flexibility is influenced by cross-sectional area and geometric eccentricity. R-phase files generally have higher flexibility and lower stress, making them more resistant to fatigue than austenite files.
Arbab-Chirani *et al.* [76]	Commercial files: Hero, HeroShaper, ProFile, Mtwo, and ProTaper F1	CAST3M/ Bending and torsion	The force and torque required for each file to deform were significantly different.
He and Ni[77]	Commercial files: V-Taper	Not specify/ Bending and torsion	Torsional stiffness can be increased by reducing pitch and increasing cross-sectional areas.
Baek *et al.* [78]	Triangle, rectangle, slender rectangle, and square	Abaqus/ Torsion	Torsional stiffness can be increased by reducing pitch and increasing cross-sectional areas.
Versluis *et al.* [79]	Triangle, slender rectangle, rectangle, and square	MSC.Marc/ Bending	The center-core area shows a more consistent correlation with flexural stiffness than the cross-sectional area. Although stiffness requirements in torsion and flexure are conflicting, flexural stiffness is directly related to rotational stiffness.
Ha *et al.* [80]	Commercial file and the modified models: ProTaper Next	Abaqus/ Bending and torsion	For rectangle-based models, bending flexibility decreases as the off-center distance increases.
Martins *et al.* [81]	Commercial files: ProTaper Next X1 and X2	Abaqus/ Bending and torsion	Eccentric files do not have superior flexibility, but lower stress is observed under bending load. The off-axis geometry does not affect torsional resistance.
Kim *et al.* [82]	Files with and without spring machining into the file shafts	Ansys/ Bending and torsion	A spring on the shaft of rotary files improves torsional resistance and bending flexibility.
Santos *et al.* [83]	Commercial files: Mtwo, RaCe, and PTU F1	Abaqus/ Bending and torsion	A good agreement between the finite element simulation and experiment results was achieved.

6.2. Prediction of Fatigue Life

Only a few studies employed FEA fatigue simulation to investigate fatigue behaviors of rotary files. Cheung *et al.* [93] determined the bending fatigue life of triangular and square cross-sectional rotary files made of stainless steel and the NiTi alloy. The fatigue life was determined based on the strain-life approach available in the fatigue module of the Ansys software. The Coffin–Manson equation for the strain-life relationship was adopted. The bending load on the file was simulated with a cantilever beam model. It was found that NiTi files can sustain a higher number of cyclic bending loads compared to stainless steel files. The fatigue life of the files was also influenced by the cross-sectional configurations of the files. A similar fatigue study of ProFile GT and GT Series X (GTX) rotary files [94] determined the fatigue life of the files based on the strain-life approach with fully reversed loading. The equivalent or von Mises stress was used without mean stress correction theory. Similar to the previous study, a flexural load on the files was simulated by applying a 1-N force at the tip of the file. However, only a simple static bending load was applied in the previous study. In this study, a better approximation of the loading conditions was achieved by applying a point load in rotational steps, resulting in a simultaneous sinusoidal load in two reference orthogonal directions. This study found that GTX files that were fabricated from M-wire alloy were more flexible and can withstand the fatigue load more than conventional files, especially in conditions with extensive deformation. In cases of small deformation, both GT and GTX files performed comparably well in terms of fatigue behavior. A recent study by Roda-Casanova *et al.* [95] applied a more realistic loading condition to study the fatigue behavior of dental files. The specimens were inserted into a simulated root canal that was modelled as a rigid and immovable tube with a taper size and curvature. The cross-section at the shaft end of the file was assumed to be a rigid surface with a reference node assigned on the surface. Boundary conditions were defined on the rigid surface and on the reference node. The study utilized the Coffin–Manson relation in the fatigue analysis, similar to the previous two studies; however, the critical plane concept was also adopted due to the fact that the Coffin–Manson relation was derived based on a uniaxial strain configuration. Therefore, the maximum principal strain was used in the analysis and the total strain range, $\Delta\varepsilon_i$, was utilized with the Coffin–Manson relation to determine the fatigue life of the files. This study introduced the most realistic loading configuration for a FEA study and a comprehensive fatigue analysis. Another study that did not apply a uniaxial fatigue criterion to the problem was a study by Scattina *et al.* [96]. The authors recognized that the states of stress and strain in the rotating files were not uniaxial, so a multi-axial random fatigue criterion; that is, the C–S criterion, was adopted. The numerical predictions of the fatigue life in terms of the NCF and failure location were verified with the test results. In this study, the fatigue testing equipment was also modelled in the FEA, providing a simulated root canal for the file.

Unlike in an experimental approach, research in the field of fatigue analysis of endodontic files using a FEA method is limited. The simplest flexural fatigue analysis found in the literature modelled the rotary file as a cantilever beam under a transverse static load. A more complicated and realistic modeling of bending behavior was obtained by inserting the file into the simulated root canal. The file was then rotated to determine the strain range in the file, which was used in further fatigue analysis. The majority of the studies utilized static analysis to determine the maximum stress and strain induced in the files. The investigation did not account for dynamic effects in the analysis. A standard guideline for finite element modeling of the file under bending fatigue is required for an accurate prediction of the fatigue life. The fatigue failure criterion used for this problem is another topic that needs further investigation, including verification of the numerical approach with the experimental results.

7. Conclusions

FEA is a numerical tool that helps engineers and designers approximate solutions quickly and at relatively low cost. However, FEA modeling, which includes physical modeling, loading conditions and boundary conditions, needs to be accurate and only reflects the problem of interest. Although the FEA method has been applied to investigate the mechanical responses of dental rotary files for more than 20 years, the modeling of problems has varied from study to study. The solid model of the files was obtained from known configurations of the files using CAD software or from CT-scanned images. The quality of the solid model obtained from both approaches is comparable and successfully meshed to form a FEA model. The diversity of FEA in the literature involved simulation of the boundary and loading conditions. Although it is widely accepted that loads applied to a rotary file are mostly flexural and bending loads, modeling these loads from FEA is not straightforward. There were several loading configurations used in previous studies for both flexural and torsional loading in the files. Although there is an ISO standard for endodontic instruments, the research community has not agreed on the use of specific load and boundary conditions. Moreover, the degree of deviation of a FEA model from a rotary file in a real-world application is not known. Therefore, solutions of a FEA method may be suitable only for a comparative study. Specifically, FEA solutions can be effectively used to compare the behavior of a model with that of another model, but the solutions may not be accurate if the absolute behaviors of the file are required. To obtain an accurate prediction of the mechanical behaviors of the files, more realistic load and boundary conditions are required. Therefore, the determination of accurate load and boundary conditions for finite element modeling could be a focus of future studies.

Similar to applications of FEA to other biomechanics problems, a majority of research in the field of endodontic files using FEA aims at determining stress distributions for the files. From the stress distribution obtained, the strength and failure of the rotary files can be determined. The effects of cross-sectional patterns and material properties on stress distributions have been investigated, along with a comparison of stress distributions in commercially available rotary files. Although several FEA studies have appeared in the literature, there is a lack of experimental studies that verified FEA solutions. A direct comparison between the stress of a FEA and the experimental measurement may not be feasible with a conventional measurement technique, because the sample is very small. The non-contact strain measurement technique could be a more suitable alternative. Another observation on FEA studies is that there is a deficiency in parametric studies. Most studies compared the stress distributions of rotary files with different physical appearances or compared the stress induced in different file models. The effects of each physical parameter on the stress distributions of the rotary files need to be studied. These studies would be a guide for designers to select and vary a particular parameter to achieve the desired mechanical behaviors.

The studies involved in investigating the flexibility and stiffness of rotary files are similar to the studies involved in determining stress distributions. Most studies determined the flexibility and stiffness of the files and investigated the effects of material properties and geometric configurations of the files. Heat-treated NiTi alloys exhibited higher flexibility than that of a conventional alloy. The geometric configurations of files affected the flexibility including cross-sectional geometries, taper, pitch, helix angle, flute length, eccentricity of the cross-sectional area and modification of the shaft portion. Similar to the case of stress analysis, the experimental verification of FEA results on flexibility and stiffness problems of the files is needed. Future research opportunities on the topic of flexibility and stiffness of dental files include optimization of the flexibility or stiffness of rotary files. To obtain sufficient flexibility so that the file can be inserted into the root canal and, at the same time, to obtain adequate stiffness so that cutting efficacy and other competences are optimal, the appropriate flexibility and stiffness of the file must be determined. FEA can be performed to investigate, for example, cutting efficiency and debris removal ability so that the optimal flexibility and stiffness of the file can be determined.

Unlike experimental tests for the NCF of rotary files, only a handful of studies that applied the FEA method to the fatigue problem of the rotary file can be found in the literature. Additional studies of FEA and experimental verification of the FEA results are required for this type of problem before the FEA method can be confidently applied to the fatigue problem of rotary files. There are many fatigue theories available in the literature and they have been applied to engineering problems. However, only the Coffin–Manson equation for the strain-life fatigue analysis was used for the fatigue problems of the files. Most of the fatigue analysis that appeared in the literature was based on static analysis; that is, the flexural load on the model was achieved by a constant transverse load. It would be interesting to perform a fatigue analysis by considering the maximum alternating stress during operation of the instrument. In this case, the root canal must also be modelled in the FEA.

In conclusion, the FEA method has been applied to examine the mechanical behaviors of dental rotary files. It is very useful for researchers and designers to obtain a preliminary estimate of the mechanical behaviors and life of the files. The accuracy of FEA has depended on the logicality of the model, the accuracy of the boundary and load conditions, the precision of the theory used in the analysis and the correctness of the interpretation of the results. Modeling of loading and boundary conditions is a challenging topic for future study. A more realistic modeling of the loaded rotary file can be obtained by inserting the file into a root canal model, rather than applying loads directly to the file. With appropriate implementation of the FEA, the results of a FEA method can be used in the design and optimization of new instruments.

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