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ORIGINAL ARTICLE

Cyclic Fatigue Resistance and Surface Roughness of Rotary NiTi Instruments after Simulated Clinical Use in Curved Root Canals – An Atomic Force Microscopy Study

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ABSTRACT
Objective: To examine the cyclic fatigue resistance and surface topography of TruNatomy and ProTaper Gold nickel-titanium rotary files and evaluate the presence of alterations to surface topography following instrumentation in simulated curved canals. **Material and Methods:** Twenty-four nickel-titanium instruments, twelve each of TN and PTG file systems, were evaluated for cyclic fatigue resistance. The rotary files were rotated in a simulated root canal with standardized diameter, angle of curvature, and radius of curvature in a custom-made cyclic fatigue testing device until the instrument fracture occurred. The time to fracture for each instrument was recorded with a stopwatch; in seconds in each group. Fractured instruments were subjected to atomic force microscopy analysis measuring the average roughness and the root mean square values to investigate surface features of endodontic files. Mean values and standard deviation were calculated. Data were analyzed using the Mann-Whitney U test. **Results:** Time to fracture was marginally higher in PTG instruments than in the TN file systems. PTG files exhibited higher surface roughness when compared with TN files ($p<0.05$). **Conclusion:** TN file system had a higher cyclic fatigue resistance than PTG. Cyclic fatigue causing file breakage did affect the surface topography of the files. PTG files showed a higher surface porosity value than the TN files.

Keywords: Endodontics; Microscopy, Atomic Force; Tooth; Dental Alloys; Torque.

Introduction

The advent of nickel-titanium (NiTi) instruments has revolutionized endodontics, aiding in the enhanced success of root canal therapy [1]. NiTi instruments have substantial superiority in their physical properties, addressing rigidity and cyclic fatigue analogous with stainless steel files [2]. In addition, NiTi files reported reduced procedural errors such as zipping, ledge formation, or apical extrusion due to its property of superelasticity [3-5]. Despite the advantage of preferable physical properties, NiTi alloys pose fracture risk without evident signs [6]. However, in recent times, the NiTi alloys manufactured with precise thermal treatments have enhanced the mechanical properties of endodontic files [7,8].

TruNatomy (TN; Dentsply Sirona, Maillefer, Ballaiges, Switzerland) has a slim NiTi wire design with an off-centred cross-section, operating at a higher speed with less torque. The instrument is made of a NiTi heat-treated wire that provides increased flexibility, allowing pre-curving of the file when needed. Due to its superior canal-centring ability, the instrument is designed to adapt to the canal, not the other way around. ProTaper Gold (PTG, Dentsply Tulsa Dental Specialties, Tulsa, OK, USA) has been developed with metallurgical advancement of gold wire. The gold appearance is attributed to the heat-treated NiTi metal followed by slow cooling, improving the strength and flexibility of the ProTaper files. It has a convex triangular cross-section that tapers progressively to improve the cutting efficiency while reducing the rotational friction between the blade, file and dentine [9-12].

The two predominant reasons for intracanal instrument separation are firstly due to cyclic fatigue ascribed to NiTi files when rotated freely within a curved canal at the point of maximum flexure and secondly due to excess torsional load exceeding the elastic and plastic properties of the NiTi rotary instrument. Torsional failure usually occurs when the tip of the instrument is engaged chiefly and blocked in the dentin walls whilst the instrument continues to rotate and is affected by varied factors. The factors resulting in torsional fatigue range from errors in the manufacturing process to the clinical use, in addition to the influence of flexural stresses, whereas factors attributing to the cyclic fatigue of NiTi files rotating in a curved root canal, include anatomy of the canal, biomechanical preparation techniques followed and sterilization procedures, size, taper, cross-section, and instrument design, as well as the manufacturing technique [13,14]. However, the main disadvantage is that cyclic fatigue-related fractures occur physically without distortion [15].

Various techniques have been used to examine the surfaces of NiTi files following cyclic fatigue, with scanning electron microscope (SEM) analysis being most routinely used for evaluation. However, atomic force microscopy (AFM) can also evaluate the topographic features of the NiTi files used in root canal treatment, with the advantage of no additional preparation of samples to evaluate the topography of the file surface so that a three-dimensional image of the surface of the specimen can be procured with an array of conditions under high spatial resolutions [16]. The principle of Atomic Force Microscopy is to study the surface of a sample by probing it with a cantilever with a flexible, sharp tip. Evaluating the forces in the interaction between the cantilever tip and surface of the sample provides information about the sample's qualitative and quantitative surface topography [7,8].

The present study aimed to examine the cyclic fatigue resistance of TruNatomy and Protaper Gold NiTi rotary files and evaluate the presence of alterations on the fractured surfaces to the surface topography of the files in simulated curved root canals.

Material and Methods

Sample Selection

Twelve samples of two engine-driven NiTi instruments were tested: TruNatomy (TN; Dentsply Sirona, Maillefer, Ballaiges, Switzerland) and ProTaper Gold (PTG, Dentsply Tulsa Dental Specialties, Tulsa, OK, USA). Power calculation was done using G*Power 3.1 Software for Windows (Heinrich-Heine-Universität, Düsseldorf, Germany). Twenty-four samples, 12 per group, were indicated to be the ideal sample size estimated to observe significant differences. The rotary files were examined under a stereomicroscope (Olympus BX43, Olympus Co., Tokyo, Japan) at ×20 magnification for defects and deformities before testing.

Cyclic Fatigue Test

Twenty-four Ni-Ti files (12 TN and 12 PTG files) were instrumented in a fabricated custom stainless steel curved metal block with a 2.0 mm wide, 60-degree curve and a 2.5 mm radius (Figure 1). The block had dimensions of length 26 mm, height 25 mm and depth 10 mm. It was covered with acrylic glass to observe the broken files and extract them (Figure 1). The cyclic fatigue resistance test was conducted by continuous instrumentation of each file system in the mould up until fracture. According to the manufacturer's instructions, the files were instrumented using X-Smart rotary endodontic motor (X-Smart; Dentsply Maillefer) with a contra-angle (16 : 1 reduction). As a result, instrument fracture was detected visually.

Figure 1. Cyclic fatigue testing device.

TN Prime File with tip size 26 and 0.04 taper and PTG with tip size 25 and 0.08 taper were selected. All files had the same length (25 mm). Each file was rotated at a 500 rpm and 300 rpm rotational speed until it separated in the simulated curved stainless-steel canal. The timing on the stopwatch was initiated as the motion started following the precise positioning of each instrument into the simulated canal. The time was calculated until the fracture was detected visually. A 2.5× magnifying Galilean loupes with LED light (Heine Optotechnik GmbH & Co., Gilching, Germany) was used to establish the time of failure. The simulated canal was covered with a tempered glass frame to prevent slipping of the instruments, also enhancing observation of the instruments. The contra-angle handpiece was fixed to allow precision in the placement of each instrument in the simulated canal standardizing the three-dimensional positions of the instruments. A single operator conducted instrumentation for all the instruments. For each instrument, the time to fracture in seconds was recorded.

Surface Evaluation

To evaluate the surface roughness, all samples were examined under Atomic Force Microscope (Park NX20, Park Systems Corp, Suwon, Korea). An antimony doped silicon probe with a 15mm-20mm tip radius in the non-contact mode was used. The variations in the vertical position of the silicon tip provided the height of the images and registered them as bright and dark zones. A Constant tip-sample 'tap' was used by constant oscillation amplitude. Digital scans (15 × 15 μm in size) were obtained for each surface and recorded at a slow scan rate of 0.7 HZ. The average roughness (Ra) and root mean square (RMS) values were obtained in order to evaluate the surface features of endodontic files. Ra and RMS values indicated the variations in vertical surface topography. An increase in values was suggestive of alterations on the surfaces of the NiTi instruments due to the separation in simulated curved canals.

Statistical Analysis

The data collected was analyzed, and the mean and standard deviation (SD) were calculated. Differences among groups were statistically evaluated with Man Whitney U Test. Data were statistically analyzed using the SPSS 17.0 software (SPSS Incorporated, Chicago, IL, USA).

Results

The surface morphological changes of the selected files were examined post instrument fracture. For the surface roughness changes, the surface roughness area (Ra), root mean square (RMS), and peak to valley (Rpv) were evaluated using atomic force microscopy (AFM) imaging. The time taken to fracture was significantly higher in TN files than in the PTG files ($p<0.05$) (Table 1).

The 3D images of the TN and PTG files are in Figure 2. The images depicted an increase in the surface roughness of the PTG files compared to the TN after file separation. A significant difference was observed in the overall surface roughness, surface mean square and roughness profile elements between the TN and PTG files. The TN system (Figures 2D, E, F) exhibited lesser surface roughness change on separation when compared with the PTG files (Figures 2A, B, C).

Table 1. Means and standard deviations of time to fracture, root mean square (RMS), average roughness (Ra) and Rpv (peak to valley) of PTG and TN instruments.

Variables		N	Mean±SD	Median (IQR)	Range	Mann-Whitney U	p-value
Time to Fracture	TruNatomy	12	270.78±73.04	290.24 (216.71,321.9)	144.23-386.31	52.000	0.248
	Protaper Gold	12	229.14±160.47	155.37 (111.87,418.23)	60.72-461.51		
RMS	TruNatomy	12	0.34±0.1	0.34 (0.25,0.43)	0.18-0.45	71.500	0.977
	Protaper Gold	12	0.34±0.1	0.32 (0.28,0.43)	0.2-0.51		
Ra	TruNatomy	12	0.28±0.09	0.26 (0.21,0.36)	0.14-0.39	64.000	0.644
	Protaper Gold	12	0.27±0.07	0.27 (0.23,0.32)	0.13-0.36		
Rpv	TruNatomy	12	2.44±0.76	2.47 (1.94,3.19)	1.19-3.39	63.000	0.603
	Protaper Gold	12	2.21±1.09	2.37 (1.77,2.71)	0.33-3.82		

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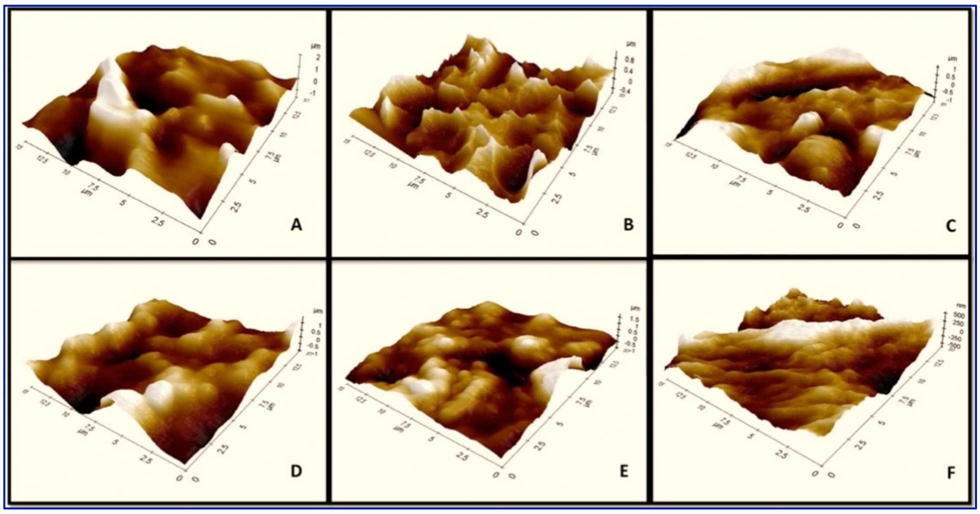

Figure 2. Three-dimensional atomic force microscopy (AFM) image of Protaper Gold (A, B, C) and TruNatomy (D, E, F) instruments.

Discussion

Intracanal separation of rotary instruments is considered a severe mishap as the separated segments limit the access of irrigants and irrigant delivery systems into the root canal system resulting in inadequate disinfection of the root canal system, in turn leading to insufficient elimination of microorganisms [17]. Hence, evaluating the cyclic fatigue of the rotary files and analyzing the surface roughness of the separated instruments is a critical subject always densely discussed in the literature [18-20]. Microscopic cracks and defects are established to play a fundamental role in the separation of instruments [21]. It is also proven that the porosities on the surface of the NiTi rotary files lead to fractures in clinical practice, especially in curved root canals [22]. Inspection of defects on files solely is not a reliable method to assess the surface changes. Despite its superelasticity, the NiTi rotary files tend to fracture during clinic use, more so without any prior indications of permanent deformations [16]. Therefore, analyzing and understanding the feature of the surface changes of files after their separation will primarily provide information regarding the use of the files in clinical practice.

In the present study, an Atomic Force Microscope was used to perform both qualitative and quantitative analyses of the surface features of the files. Scanning Electron Microscopes (SEM) and Atomic Force Microscopes (AFM) are extensively used to examine the surface changes in the rotary files [23-25]. However, SEMs mainly provide two-dimensional topographic images of the samples, making it impossible to quantitative examine the surface irregularities. Overcoming these limitations, the AFMs provide three-dimensional images, which helps determine and evaluate the quantitative data [25]. Existing literature has suggested using both artificial canals and natural canals of permanent teeth [22,24,26]. In the present study, artificial canals were preferred to minimize the variations caused by the anatomy of the natural teeth and to ensure standardization of the diameter of the root length and the curvature in terms of angle and radius [26]. The root canal anatomy of the artificial simulated curved root canal was determined by Pruett's method [27].

Numerous variables affect the fracture resistance of Nickel-titanium rotary instruments, namely the composition of the alloy, methods of manufacturing them, the cross-sectional geometry and flute designs [28]. However, to enhance the performance of instruments during root canal shaping, including the cyclic fatigue resistance, thermomechanical technology is frequently used to improve the transformation patterns and microstructures of the NiTi instruments [29]. In the present study, TN file systems exhibited more excellent cyclic fatigue resistance than the PTG systems. The results obtained are in accordance with studies done by Rashid and AI-Gharrawi [30] and Riyahi et al. [31], which evaluated the Number of cycles to fracture in simulated canals. However, to maintain a realistic time-frame of clinical practice and considering the mean life of rotary nickel-titanium instruments, the contact time of the instrument till it fractured was considered in the present study.

TN file system was analyzed to evaluate whether the novel advancement with thermomechanical technology of the instrument has helped enhance the quality of the file system, possibly improving the instrument's resistance to cyclic fatigue. The design attributes of the TN file system comprises the use of a 0.8 mm special heat-treated wire nickel-titanium wire as an alternative to the 1.2 mm nickel-titanium wire commonly used. The file system is operated at a higher speed of 500rpm. Due to the properties of increased flexibility and cyclic fatigue resistance, the TN files are supposed to be decreasing the risk of file separation [11]. The Prime TN file used in the present study has a tip size of 26 with a 0.04 taper. In the present study file, Prime TN was compared with the PTG with tip size 25 and taper 0.08 taper. Both the file systems were chosen knowing it has a different taper as the primary goal of the present study is to analyze the performance of the two different file systems in term of resistance to cyclic fatigue. However, previous reports in the literature have also compared the cyclic fatigue resistance of files with different tapers [14]. PTG exhibited lesser resistance to fracture in comparison to the TN files. The results may be attributed to the characteristics of the file design, type of thermal treatment employed, the type of alloy and the vol per mm of the rotary file representing the metal mass of the instrument [26,32,33]. PTG files comprise a nickel-titanium alloy with advanced metallurgy with two-phase transformation. The manufacturer's thermomechanical processing of the TN file system is by a special heat treatment nickel-titanium wire, which may have played a significant role in improving its resistance to cyclic fatigue. Although, the details about the type of nickel-titanium wire used has not been mentioned [29]. TN shaping file has an off-centred parallelogram cross-sectional design; hence it might be speculated that this design compared with PTG convex triangle cross-section, could contribute to the higher cyclic fatigue resistance of the TN files [15,34,35]. It is established that the instrument's cross-sectional design directly influences the metal mass values [32,33]. The design of the two systems evaluated in the present study is varied. PTG in the point of maximum curvature of the artificial canals has a greater mass than TN due to the greater taper of PTG. However, the present study results could be due to the different cross-sectional designs of the instruments despite the same tip and taper diameter. The present study results are in accordance with a study done by Di Nardo et al. [32] and Grande et al. [33], confirming a significant interrelationship between the cross-section and cyclic fatigue resistance of NiTi rotary instruments.

According to the results obtained from the present study, PTG files have exhibited higher surface roughness; Ra values than the TN files. The increased surface roughness observed in the PTG files following file separation suggests that these files are more inclined towards the deterioration of surface features than the TruNatomy files. It has been established that the variations in the surface roughness of the nickel-titanium rotary files are fundamental in the initiation of cracks, causing file separation [22]. In the present study, there exist distinct variations in the surface topography of the files examined. The variations can be attributed to the various metal alloys and the thermal treatment used during the manufacturing process.

Very few studies have evaluated the cyclic fatigue resistance of TN files followed by surface roughness evaluation, especially by atomic force microscopy, which has given a precise insight into the surface changes occurring during instrument separation in curved canals. Also, the study evaluated the cyclic fatigue resistance by analyzing the instrument's contact time, providing a clinical and practical outlook for the dental clinicians whilst practising rotary endodontics. However, discretion and further studies including various factors are needed before extrapolating the results of the present in vitro study into clinical practice as the factors leading to cyclic fatigue are complex. It would be difficult to rely solely on a single variable to determine the cyclic fatigue resistance. Both the file systems tested were subjected to various thermal treatment manufacturing procedures and had different geometric design characteristics. Further studies evaluating the varied factors associated with cyclic and torsional fatigue resistance, modes of fracture with multiple apparatus designs in simulated canals, and root dentin are necessary to understand instrument separation's clinical failure patterns.

Conclusion

The TruNatomy file system had a better cyclic fatigue resistance than the Protaper Gold file system. Cyclic fatigue on the file systems affected the surface topography of the files. The Protaper Gold files showed higher surface porosity values than the TruNatomy files. Nonetheless, both the file systems possess various metallurgic properties, manufacturing procedures, thermal treatments, cross-section design characteristics and tapers. Hence, a single variable cannot be held responsible for the fracture of instruments. However, it is fundamental to note that the clinical situation involves complex stresses, necessitating further studies to evaluate the microstructure and fracture pattern of the instruments.

Authors' Contributions

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PS	https://orcid.org/0000-0002-8045-1893	Methodology, Validation, Investigation, Writing - Review and Editing and Visualization.
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All authors declare that they contributed to critical review of intellectual content and approval of the final version to be published.

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None.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability

The data used to support the findings of this study can be made available upon request to the corresponding author.

References

[1] Cheung GS, Liu CS. A retrospective study of endodontic treatment outcome between nickel-titanium rotary and stainless steel hand filing techniques. J Endod 2009; 35(7):938-43. https://doi.org/10.1016/j.joen.2009.04.016

[2] Walia HM, Brantley WA, Gerstein H. An initial investigation of the bending and torsional properties of Nitinol root canal files. J Endod 1988; 14(7):346-51. https://doi.org/10.1016/s0099-2399(88)80196-1

[3] Gambarini G, Grande NM, Plotino G, Somma F, Garala M, De Luca M, et al. Fatigue resistance of engine-driven rotary nickel-titanium instruments produced by new manufacturing methods. J Endod 2008; 34(8):1003-5. https://doi.org/10.1016/j.joen.2008.05.007

[4] Plotino G, Ahmed HM, Grande NM, Cohen S, Bukiet F. Current assessment of reciprocation in endodontic preparation: a comprehensive review - Part II: properties and effectiveness. J Endod 2015; 41(12):1939-50. https://doi.org/10.1016/j.joen.2015.08.018

[5] Karataş E, Arslan H, Büker M, Seçkin F, Çapar ID. Effect of movement kinematics on the cyclic fatigue resistance of nickel-titanium instruments. Int Endod J 2016; 49(4):361-4. https://doi.org/10.1111/iej.12453

[6] Sattapan B, Nervo GJ, Palamara JE, Messer HH. Defects in rotary nickel-titanium files after clinical use. J Endod 2000; 26(3):161-5. https://doi.org/10.1097/00004770-200003000-00008

[7] Topuz O, Aydin C, Uzun O, Inan U, Alacam T, Tunca YM. Structural effects of sodium hypochlorite solution on RaCe rotary nickel-titanium instruments: an atomic force microscopy study. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2008; 105(5):661-5. https://doi.org/10.1016/j.tripleo.2007.11.006
[8] Valois CR, Silva LP, Azevedo RB. Atomic force microscopy study of stainless-steel and nickel-titanium files. J Endod 2005; 31(12):882-5. https://doi.org/10.1097/01.don.0000164132.27285
[9] Khalil WA, Natto ZS. Cyclic fatigue, bending resistance, and surface roughness of ProTaper Gold and EdgeEvolve files in canals with single- and double-curvature. Restor Dent Endod 2019; 44(2):e19. https://doi.org/10.5395/rde.2019.44.e19
[10] Hieawy A, Haapasalo M, Zhou H, Wang ZJ, Shen Y. Phase transformation behavior and resistance to bending and cyclic fatigue of ProTaper Gold and ProTaper Universal instruments. J Endod 2015; 41(7):1134-8. https://doi.org/10.1016/j.joen.2015.02.030
[11] Dentsply Sirona Inc. TruNatomy Brochure. Available from: https://assets.dentsplysirona.com/flagship/en/explore/endodontics/brochure/trunatomy/END-TruNatomy-Brochure.pdf. [Accessed on May 22, 2021].
[12] Plotino G, Grande NM, Mercadé Bellido M, Testarelli L, Gambarini G. Influence of temperature on cyclic fatigue resistance of ProTaper Gold and ProTaper Universal rotary files. J Endod 2017; 43(2):200-2. https://doi.org/10.1016/j.joen.2016.10.014
[13] Zanza A, Seracchiani M, Di Nardo D, Reda R, Gambarini G, Testarelli L. A Paradigm shift for torsional stiffness of nickel-titanium rotary instruments: a finite element analysis. J Endod 2021; 47(7):1149-56. https://doi.org/10.1016/j.joen.2021.04.017
[14] Gambarini G, Miccoli G, Seracchiani M, Khrenova T, Donfrancesco O, D'Angelo M, et al. Role of the flat-designed surface in improving the cyclic fatigue resistance of endodontic NiTi rotary instruments. Materials 2019; 12(16):2523. https://doi.org/10.3390/ma12162523
[15] Elsewify TM, Saber SM, Plotino G. Cyclic fatigue resistance of three heat-treated nickel-titanium instruments at simulated body temperature. Saudi Endod J 2020; 10(2):131-6. https://doi.org/10.4103/sej.sej_122_19
[16] Özyürek T, Yılmaz K, Uslu G, Plotino G. The effect of root canal preparation on the surface roughness of WaveOne and WaveOne Gold files: atomic force microscopy study. Restor Dent Endod 2018; 43(1):e10. https://doi.org/10.5395/rde.2018.43.e10
[17] Haapasalo M, Udnæs T, Endal U. Persistent, recurrent, and acquired infection of the root canal system post-treatment. Endod Top 2003; 6(1):29-56. https://doi.org/10.1111/j.1601-1546.2003.00041.x
[18] Keskin C, Inan U, Demiral M, Keleş A. Cyclic fatigue resistance of Reciproc Blue, Reciproc, and Waveone Gold reciprocating instruments. J Endod 2017; 43(8):1360-3. https://doi.org/10.1016/j.joen.2017.03.036
[19] Yılmaz K, Uslu G, Gündoğar M, Özyürek T, Grande NM, Plotino G. Cyclic fatigue resistances of several nickel-titanium glide path rotary and reciprocating instruments at body temperature. Int Endod J 2018;5 1(8):924-30. https://doi.org/10.1111/iej.12901
[20] Gündoğar M, Özyürek T. Cyclic fatigue resistance of OneShape, HyFlex EDM, WaveOne Gold, and Reciproc Blue Nickel-titanium Instruments. J Endod 2017; 43(7):1192-6. https://doi.org/10.1016/j.joen.2017.03.009
[21] Alapati SB, Brantley WA, Svec TA, Powers JM, Mitchell JC. Scanning electron microscope observations of new and used nickel-titanium rotary files. J Endod 2003; 29(10):667-9. https://doi.org/10.1097/00004770-200310000-00014
[22] Alapati SB, Brantley WA, Svec TA, Powers JM, Nusstein JM, Daehn GS. SEM observations of nickel-titanium rotary endodontic instruments that fractured during clinical Use. J Endod 2005; 31(1):40-3. https://doi.org/10.1097/01.don.0000132301.87637.4a
[23] Türker SA, Sağlam BC, Koçak MM, Koçak S. The effect of glide path on the surface quality of new and used rotary and reciprocating single files: OneShape versus WaveOne. Scanning 2014; 36(6):608-13. https://doi.org/10.1002/sca.21161
[24] Caballero H, Rivera F, Salas H. Scanning electron microscopy of superficial defects in Twisted files and Reciproc nickel-titanium files after use in extracted molars. Int Endod J 2015; 48(3):229-35. https://doi.org/10.1111/iej.12304
[25] Cazaux J. Recent developments and new strategies in scanning electron microscopy. J Microsc 2005; 217(Pt 1):16-35. https://doi.org/10.1111/j.0022-2720.2005.01414.x
[26] Fatma Y, Ozgur U. Evaluation of surface topography changes in three NiTi file systems using rotary and reciprocal motion: an atomic force microscopy study. Microsc Res Tech 2014; 77(3):177-82. https://doi.org/10.1002/jemt.22325
[27] Pruett JP, Clement DJ, Carnes DL Jr. Cyclic fatigue testing of nickel-titanium endodontic instruments. J Endod 1997; 23(2):77-85. https://doi.org/10.1016/S0099-2399(97)80250-6
[28] Kim TO, Cheung GS, Lee JM, Kim BM, Hur B, Kim HC. Stress distribution of three NiTi rotary files under bending and torsional conditions using a mathematic analysis. Int Endod J 2009; 42(1):14-21. https://doi.org/10.1111/j.1365-2591.2008.01481.x
[29] Uslu G, Özyürek T, Yılmaz K, Gündoğar M. Cyclic fatigue resistance of R-Pilot, HyFlex EDM and PathFile nickel-titanium glide path files in artificial canals with double (S-shaped) curvature. Int Endod J 2018; 51(5):584-9. https://doi.org/10.1111/iej.12846

[30] Rashid SA, AI-Gharrawi HA. Cyclic fatigue of trunatomy nickel-titanium rotary instrument in single and double curvature canals: a comparative study. World J Dent 2021; 12(1): 28-31.
[31] Riyahi AM, Bashiri A, Alshahrani K, Alshahrani S, Alamri HM, Al-Sudani D. Cyclic fatigue comparison of TruNatomy, Twisted File, and ProTaper Next rotary systems. Int J Dent 2020; 2020:3190938. https://doi.org/10.1155/2020/3190938
[32] Di Nardo D, Gambarini G, Seracchiani M, Mazzoni A, Zanza A, Del Giudice A, et al. Influence of different cross-section on cyclic fatigue resistance of two nickel–titanium rotary instruments with same heat treatment: An in vitro study. Saudi Endod J 2020; 10(3):221-5. https://doi.org/10.4103/sej.sej_124_19
[33] Grande NM, Plotino G, Pecci R, Bedini R, Malagnino VA, Somma F. Cyclic fatigue resistance and three-dimensional analysis of instruments from two nickel-titanium rotary systems. Int Endod J 2006; 39(10):755-63. https://doi.org/10.1111/j.1365-2591.2006.01143.x
[34] Shen Y, Zhou HM, Zheng YF, Peng B, Haapasalo M. Current challenges and concepts of the thermomechanical treatment of nickel-titanium instruments. J Endod 2013; 39(2):163-72. https://doi.org/10.1016/j.joen.2012.11.005
[35] Hanbazaza NS, Abuhaimed TS. Influence of kinematics on the cyclic fatigue of ProTaper Gold and WaveOne Gold. Saudi Endod J 2020; 10(2):145-51. https://doi.org/10.4103/sej.sej_132_19