ASDJ
AINSHAMS DENTAL JOURNAL

Print ISSN 1110-7642
Online ISSN 2735-5039

AIN SHAMS DENTAL JOURNAL
Official Publication of Ain Shams Dental School
June2021 • Vol. XXIV

Evaluation of cyclic fatigue of three different Rotary Nickel Titanium Systems

Hisham Khaled Fouad[1], *Ahmed Abd Elrahman Hashem*[2], *Tarek Moustafa Abdel Aziz*[3].

Abstract

To overcome the inconveniences of manual filing systems, nickel-titanium (NiTi) rotary shaping techniques were developed. The study was conducted to evaluate the cyclic fatigue resistance and martensitic/austenitic phase at body and room temperatures for HyFlex EDM, M-Pro, Denjoy i3Gold files.

Twenty files of each system were used. Ten of them were used at room temperature and ten were used at body temperature. Dynamic cyclic fatigue testing was performed with a specific device, which allowed the instruments to rotate freely inside a Stainless-Steel artificial canal while providing an axial movement with amplitude of 3mm up and down movement. The number of cycles to failure (NCF) was calculated.

A Sample with weight 10 to 15 gm of each instrument was evaluated using DSC. The DSC analyses were conducted over a temperature ranging from 0o C to 60o C.

The results showed higher cyclic fatigue of HyFlex EDM followed by Denjoy i3Gold and M-Pro showed the lowest values for both room and body temperatures. Temperature showed no effect on cyclic fatigue for all instruments within this study. The differential scanning calorimetry confirmed the presence of the martensitic phase in Hyflex EDM, M-Pro and Denjoy i3Gold at room temperature and body temperature.

Keywords: cyclic fatigue ; Rotary Nickel Titanium ; Hyflex EDM ; M-Pro ; Denjoy i3Gold

1. Endodontic department, Ain Shams University, Cairo, Egypt
2. Professor Endodontic department, Ain Shams University, Cairo, Egypt
3. Lecturer Endodontic department, Ain Shams University, Cairo ,Egypt

Introduction:

Root canal cleaning and shaping are important phases in endodontic therapy. The objectives of instrumentation include; debriding the root canal system, continuously tapering in a conical form, and maintain the original shape and position of the apical foramen. Conventional instrumentation was performed by hand filing with stainless steel files. However, the stiffness of these files (which increases with increasing sizes) causes the straightening of curved canals and results in apical enlargement, ledge formation, transportation of apical foramen, and non-tapered hourglass-shaped preparation are problems frequently observed after instrumentation. Instrumentation/procedural errors such as canal transportation, zipping, elbowing, ledging, strip, and root perforations, and file breakage may occur during instrumentation. These procedural errors may increase the risk of endodontic treatment failure. The complicated root canal anatomy further aggravates the situation. NiTi instruments offer many advantages such as maintaining the original shape of the root canal, as well as decreasing the possibilities of zipping, ledge formation, and perforation risk. It also increases the canal preparation quality and reduces the time of the endodontic sessions needed for the cleaning and shaping step. Unfortunately, the unpredictable fracture of NiTi rotary instruments, especially in curved root canals, is one of their most important disadvantages. (1)

The fracture of NiTi files during clinical use is affected by many factors including file design, rotational speed, and torque, and the angle of curvature of the canal. The file fracture occurs through two different mechanisms: torsional fatigue and cyclic fatigue. When the torsional stress exceeds beyond the elastic limit of the file, it will plastically deform and then, if the stress is still maintained, it results in the fracture of the file. In cyclic fatigue, the file fractures because of repetitive compression and tension stress at the maximum curvature point of the canal. To decrease the fracture incidence of NiTi rotary files, the manufacturers aim to improve the resistance of the files using different alloys during production, applying various heat treatments, and changing the design properties of files. (2)

HyFlex EDM (HEDM; Coltene/Whaledent, Altstätten, Switzerland) is a new-generation NiTi file system still used in continuous rotary motion. HEDM represents the evolution of the HyFlex CM (HCM; Coltene/Whaledent) that was the first file system manufactured using the controlled memory (CM) technology. Differently from the HCM, the HEDM files are produced with the CM alloy and using the electrical discharging machining (EDM) technology. Making use of electrical discharges, the file is shaped by melting and vaporizing the material with a non-contact production method.

As many GP dentists or even some endodontic specialists start to use this Chinese file as they are much cheaper and widely spread on the market. One of the most known files in the Egyptian market is the M-Pro (IMD) file system which has a convex triangular cross-section with a CM heat-treated NiTi alloy. Denjoy (dental co) is another well-known file with the CM heat-treated technology, the files have a triangular cross-section with an optimized guiding tip.

It is postulated that these different heat treatments and designs can significantly affect the in vitro resistance to cyclic fatigue of NiTi rotary instruments. That’s why, dynamic cyclic fatigue testing at different temperatures was This study was conducted to compare three types of Ni-Ti Rotary File systems: Hyflex EDM, M-Pro, and Denjoy i3Gold.

Materials and methods:

1- Cyclic fatigue fracture:

Sixty files with tip size 25 were divided into three groups according to the file system. Each group was further subdivided into subgroups, one subgroup was tested at body temperature 37°C and the other was tested at room temperature 25° C.

A custom-made cyclic fatigue-testing device was designed and assembled by M. El-Wakeel which was utilized in the study (figure1). An artificial simulated canal designed with AutoCAD Autodesk and milled from Stainless-steel with tip size #25, 8% taper, depth of the canal +0.2 mm of the maximum diameter of the instrument, 90˚ angle of curvature, 5mm radius of curvature according to the method of Pruett et al.(3), the center of curvature is 5mm from the end of the canal and the straight part is 11 mm with the total length of the canal is 16 mm (figure2). There is a missing side of the canal which is important to allow monitoring and easy replacement of files. This missing side is re-established by a piece of glass fixed in place by two hand screws.

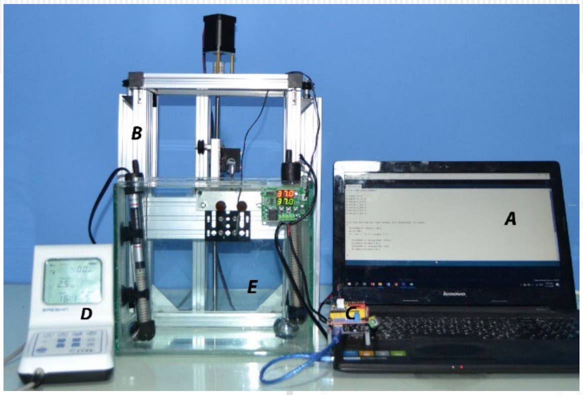

Figure 1: Cyclic fatigue testing assembly, A: custom made code, B: Custom made cyclic fatigue device, C: Arduino UNO and shield, D: Endodontic motor, E: Custom made water bath.

Figure 2: The artificial canal.

2- Structural analysis using Differential scanning calorimetry:

Three new instruments of each file system were evaluated using differential scanning calorimetry with scans ranging from approximately 60°C to 0°C to assess the phase of the file at different temperatures and transformation temperatures.

A temperature program, consisting of two heating and one cooling ramp starting from room temperature with heating/cooling rate 10 °C min^{-1} under nitrogen atmosphere at a rate of 20mL/min was applied. The samples were heated from room temperature to 60 °C, then cooled to 0 °C to obtain the cooling DSC curve, and subsequently reheated to 60 °C to acquire the heating DSC curve. The Plots were analyzed by TA Universal Analysis computer software to obtain the onset temperatures for the phase transformations, along with the enthalpy changes (ΔH) associated with these processes. The martensitic transformation-starting and transformation-finishing points (Ms, Mf) and austenitic reverse transformation-starting, transformation-finishing points (As, Af) were determined and the enthalpy changes (ΔH) were obtained from the intersection between extrapolation of the baseline and maximum gradient line of the DSC curve.

3- Statistical analysis:

Using the Minitab program one-way analysis of variance (ANOVA) and Tukey Honestly Significant

Difference (HSD) test were calculated to determine any statistical difference amongst groups, for inter-group comparison the unpaired t-test was used. In the present study, $P \leq 0.05$ was considered as the level of significance.

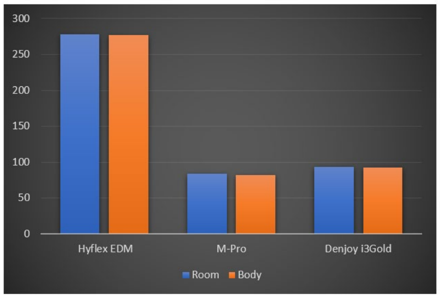

Figure 3 Hyetography showing the effect of temperature on the number of cycles to fracture

Results:

After the data were collected, tabulated, and statistically analyzed, the results of the different tests showed the following.

a. Cyclic fatigue results:

HyFlex EDM showed a significantly higher cyclic fatigue resistance than M-pro and Denjoy i3Gold in both room and body temperatures. M-Pro files showed the lower cyclic fatigue resistance results in both room and body temperatures. (figure 3) (table1)

Table 1: Number of cycles to fracture.

	Room (25° c)	Body (37° c)	P value
Hyflex EDM	278.41 ±2.09 [a]	277.33 ±1.86 [a]	0.267
M-Pro	84.28 ±3.37 [b]	81.79 ±2.23 [b]	0.087
Denjoy i3Gold	93.37 ±1.29 [c]	92.13 ±1.21 [c]	0.053
P value	0.0051×10^{-35}	0.0052×10^{-37}	

Means that do not share the same letter are significantly different.

While no statistically significant difference showed between body temperature (277.33 ±1.86) and room temperature (278.41 ±2.09) of HyFlex EDM. Also, for M-Pro there is no significant difference between body temperature (81.79 ±2.23) and room temperature (84.28 ±3.37). And also, for Denjoy i3Gold there is no significant difference was observed between body temperature (92.13 ±1.21) and room temperature (93.37 ±1.29).

b. Differential scanning calorimetry:

Hyflex EDM, M-Pro, and Denjoy i3Gold files showed A_f higher than the body temperatures. The endothermic and exothermic peaks for M-pro and Denjoy i3Gold represent the martensitic and austenitic phase change, while for Hyflex EDM OneFile represents R-phase and austenitic phase change. (table 2)

Discussion:

Investigation of properties and behavior of Chinese files is of great importance as many dentists especially general practitioners start to use those files for may be economic reasons. Although using files from well-known companies with high quality is the ideal situation. So, we choose to investigate cyclic fatigue resistance

Table 2 Phase transformation temperatures and enthalpy changes (ΔH)

	Hyflex	*M-Pro*	*Denjoy i3Gold*
M_s (°C)		36.16	37.16
M_f (°C)		33.89	34.49
ΔH (j^{-1})		1.852	1.945
A_s (°C)	43.03	35.77	39.56
A_f (°C)	53.505	46.52	43.66
ΔH (j^{-1})	2.549	1.885	1.885
R_s (°C)	44.41		
R_f (°C)	35.875		
ΔH (j^{-1})	1.1862		

and the martensitic/austenitic phase at room/body temperature for two of the most widely spread Chinese files. HyFlex EDM is used as a reference as it is one of the gold standard files in terms of cyclic fatigue resistance.

As the manufacturer starts to use the Ni-Ti alloy to fabricate endodontic files which increases the flexibility and the ability to negotiate curved canals. Regardless, file separation is still the main concern in endodontic treatment and the most predicted error. Ni-Ti is an exotic metal that does not confirm the normal rules of metallurgy.

When applying stress to St-St files it undergoes a proportional strain while Ni-Ti files start with proportional strain then it reaches a level of loading plateau, at the end, the file suddenly fails (1). Ni-Ti files have two standard modes of fracture which are fatigue failure and torsional failure (4). cyclic fatigue failure occurs when a material is subjected to repeated loading and unloading, Fatigue resistance is determined by stressing the material under specific conditions and obtaining the number of cycles required to produce failure (5).

For endodontic files, cyclic fatigue indicated by NFC (number of cycles to fracture) can be calculated by using the following formula: NCF = the duration to failure (seconds) rotating speed/60. (6)

Several in vitro study models are used for cyclic fatigue testing with several kinematics and designs without any standardization for the testing model till now. Ideally, the best model to test cyclic fatigue uses extracted teeth but actually, other non-tooth models are used as it is impossible to standardize the same natural canal for testing all files(7)(8).

A model using stainless-steel pins for cyclic fatigue testing adopted by Arias et al. (9) has the drawback of difference in trajectory for each file(7), another model using an artificial canal machined in stainless-steel block adopted in other studies(10) may have the limitation of loosely fitting instruments inside the groove. To overcome the problem Plotino et al(7) suggested a canal machined with the same size and taper of the instruments with a minimum offset of the depth to allow free rotation of the files.

In the present study, trying to mimic the clinical situation- we used a simulated canal shape model. To provide the instrument with a suitable trajectory, the canal was machined to reproduce instrument size and taper. To allow the instrument to rotate freely inside the canal, the depth of the canal was milled to the maximum diameter of the instrument +0.2 mm. The Canal was milled from St-St to avoid wearing thus preserving the same trajectory for all files. A glass cover on top of the St-St block is used to allow visualization of rotating instruments while preserving an accurate repeatable scenario as glass has higher wear resistance than Ni-Ti files.

Canal curvature and angle can affect the cyclic fatigue resistance of rotary files(11).The parameter of the simulated canal used in the present study drown by using the Pruett method (3) to increase the similarity of all files trajectory inside it. In a static model it could be easier to constrain instruments being tested in an exact trajectory, the dynamic model closely resembles a clinical situation(12)(7). The amplitude of movements in the dynamic model studies has a wide range from 1mm to 5mm. (13). While increasing the amplitude of movement increase the cyclic fatigue resistance(14), in the clinical situation it is recommended to limit the shaping to 1-3mm inside the canal(1). Therefore, in the present study, a dynamic model with a 1.5mm amplitude to simulate the pecking motion in a clinical situation was used. Only files with continuous rotation motion are used and auto-reverse mode switched off to eliminate the effect of movement on cyclic fatigue resistance.

As the temperature at which the study was conducted can affect the cyclic fatigue resistance of files(15)(16), the cyclic fatigue resistance test was performed at both body and room temperatures to simulate the clinical situation in body temperature and to evaluate the effect of temperature on each file. Generally, two models were used to perform a cyclic fatigue test at body temperature, the first model used a temperature-controlled oven(17) while the second model which is the most commonly used water bath(16). Although it may seem that the oven model leads to a more accurate temperature of the testing environment, the water bath model seems to be with a closer resemblance to the clinical condition where instruments are in contact with the irrigant.

Although room cyclic fatigue tests can be conducted in air, we chose to conduct both body and room cyclic fatigue tests using a water bath to standardize all other factors except the temperature for the same Ni-Ti system. The water bath utilized two modified aquarium heaters for better heat distribution and the heaters were controlled by an electronic temperature control unit for more accurate temperature stabilization. The temperature sensor was placed in approximation to the stainless-steel block for assurance of accurate desired temperature inside the artificial canal.

the thermometer- chanically treated NiTi-controlled memory instruments was longer in aquatic medium than in air. Such findings lend support to the present study; the the thermomechanically treated NiTi-controlled memory instru- ments was longer in the aquatic medium than in air.

Such findings lend support to the present study; the The cyclic fatigue resistance differs in the aquatic medium than in air for the thermomechanically treated NiTi-controlled memory instruments as aqueous media may serve as a heat sink, also they decrease the friction of the instruments with the canal walls which would reduce the stresses on the instrument (18)(19). In this context, synthetic oil was used as a lubricant in the current study.

Digital chronometer was used by the operator for time recording in most of the cyclic fatigue studies (20)(21), but the human factor may be the main disadvantage of this method. Arias et al. connected the simulated canal and the stop-watch to an electric circuit as an alternative method for calculation as the continuity of the circuit get interrupted and the chronometer stops when the file fractures(9). While this method is more accurate in time recording, it cannot be used inside a water bath as water will make the electric circuit always closed. So in this study, a Digital chronometer was used by the operator for time recording.

Ni-Ti has three different crystalline phases which are martensite, stress-induced martensite (superelastic), and austenite. In the Martensitic phase which can be described as a monoclinic distortion of the cubic austenitic phase, Ni-Ti is relatively soft and can be easily deformed with higher cyclic fatigue resistance. While in the austenitic phase it is non-elastic, hard, and has lower cyclic fatigue resistance. Also, Ni-Ti can exist in R-phase which is a rhombohedral distorted martensite Ni-Ti which has higher fatigue resistance than the austenitic phase and lower than the martensitic phase. The change from phase to phase is revisable in both directions by heating or cooling(1)(22)(23). From the martensitic phase to R-phase to austenitic phase by heating and reversed by cooling. Differential scanning calorimetry is the method used to provide information about the effect of temperature changes on phase transformation so the phase(s) of the Ni-Ti instrument at a given temperature can be predicted. The peaks of the heating/cooling cycle show the phase transformation of the material. (24)(25)

Our results showed a higher fatigue resistance of HyFlex EDM followed by Denjoy i3Gold and the least resistance was recorded with M-Pro. There was no significant effect of temperature on the cyclic fatigue resistance of all systems. The results might be attributed to the difference in manufacturing mode and heat treatment of files, which is consistent with previous studies who proved that the electrical discharge machining process by which the EDM file is manufactured decreased the surface defects on the instrument and the manufacturing stresses on the instrument which in turn increased the cyclic fatigue resistance(26).

M-Pro files showed the least cyclic fatigue resistance despite that the files fractured at D3 to D4 at which, the HyFlex EDM has a rectangular cross-section and 8% taper, The Denjoy i3Gold has triangular cross-section and 4% taper while the M-Pro has a convex triangular cross-section and 4% taper, that gives Denjoy i3Gold files less metal mass and less stress concentration which supposed to increase the cyclic fatigue resistance. On the other hand, cross-sectional design and core size reported in many other studies did not influence the fatigue resistance of Ni-Ti instruments(27)(28). Conversely, many studies have emphasized the significant influence of cross-sectional design on fatigue resistance (29)(30). This demonstrates that not only the cross-section factor but also the manufacturing technique, heat treatment, and alloy type affect the cyclic fatigue resistance of the instrument(31) (32)(33). The length of all fractured segments showed no significant difference which indicates that the instruments were precisely positioned in a repeatable way inside the simulated canal.

The present study showed that the austenitic transformation of HyFlex EDM, M-Pro, and Denjoy i3Gold was above body temperature. Also, HyFlex EDM showed an R-phase transformation around 37°C which was consistent with the findings of Arias, Pedllà, and Shen (16)(34). At body temperature, the existence of the R-phase/martensitic phase of HyFlex EDM, martensitic phase of M-Pro, and Denjoy i3Gold might explain the non-significance difference between room and body temperature for all files.

References:

1. McSpadden JT. Mastering endodontic instrumentation. Chattanooga, TN: Cloudland Institute. 2007. 21–28 p.
2. Parashos P, Messer HH. Rotary NiTi Instrument Fracture and its Consequences. J Endod. 2006;32(11):1031–43.
3. Pruett, John P.; Clement, David J.; Carnes DL. Cyclic Fatigue Testing of Nickel-Titanium Endodontic Instruments. J Endod. 1997;23(2).
4. Ferreira M, Ferreira H. Defects in ProFile rotary nickel-titanium files after clinical use. J Endod. 2012;6(2):113–7.
5. kenneth J., Anusavice A, Shen C, Rawls HR. Phillips' Science of Dental Materials -12th.ed. Saunders. 2013;
6. Keskin NB, Özyürek T, Uslu G, İnan U. Cyclic fatigue resistance of new and used ProTaper universal and ProTaper next nickel-titanium rotary instruments Neslihan. Saudi Endod J. 2018;(3):8–13.
7. Plotino G, Grande NM, Cordaro M, Testarelli L, Gambarini G. A Review of Cyclic Fatigue Testing of Nickel-Titanium Rotary Instruments. J Endod. 2009;35(11):1469–76.
8. Yao JH, Schwartz SA, Beeson TJ. Cyclic fatigue of three types of rotary nickel-titanium files in a dynamic model. J Endod. 2006;32(1):55–7.
9. Arias A, Samer H, Murphy S, Macorra JC de la, Govindjee S, Peters OA. Variable impact by ambient temperature on fatigue resistance of heat-treated nickel titanium

instruments. Clin Oral Investig. 2019;(23):1101–8.

10. Bouska J, Justman B, Williamson A, Delong C, Qian F. Resistance to cyclic fatigue failure of a new endodontic rotary file. J Endod. 2012;38(5):667–9.
11. Pedullà E, La Rosa GRM, Virgillito C, Rapisarda E, Kim HC, Generali L. Cyclic Fatigue Resistance of Nickel-titanium Rotary Instruments according to the Angle of File Access and Radius of Root Canal. J Endod. 2020;46(3):431–6.
12. Hülsmann M, Donnermeyer D, Schäfer E. A critical appraisal of studies on cyclic fatigue resistance of engine-driven endodontic instruments. Int Endod J. 2019;52(10):1427–45.
13. Neelakantan P, Reddy P, Gutmann JL. Cyclic fatigue of two different single files with varying kinematics in a simulated double-curved canal. J Investig Clin Dent. 2016;7(3):272–7.
14. Li UM, Lee BS, Shih CT, Lan WH, Lin CP. Cyclic fatigue of endodontic nickel titanium rotary instruments: Static and dynamic tests. J Endod. 2002;28(6):448–51.
15. Jamleh A, Yahata Y, Ebihara A, Atmeh AR, Bakhsh T, Suda H. Performance of NiTi endodontic instrument under different temperatures. Odontology. 2016;104(3):324–8.
16. Arias A, Macorra JC, Govindjee S, Peters OA. Correlation between Temperature-dependent Fatigue Resistance and Differential Scanning Calorimetry Analysis for 2 Contemporary Rotary Instruments. J Endod. 2018;44(4):630–4.
17. 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.
18. Nguyen HH, Fong H, Paranjpe A, Flake NM, Johnson JD, Peters OA. Evaluation of the resistance to cyclic fatigue among protaper next, ProTaper universal, and vortex blue rotary instruments. J Endod. 2014;40(8):1190–3.
19. Tobushi H, Nakahara T, Shimeno Y, Hashimoto T. Low-Cycle Fatigue of TiNi Shape Memory Alloy and Formulation of Fatigue Life . J Eng Mater Technol. 1999 Nov 8;122(2):186–91.
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.
21. Arias A, Perez-Higueras JJ, De La MacOrra JC. Differences in cyclic fatigue resistance at apical and coronal levels of reciproc and waveone new files. J Endod. 2012;38(9):1244–8.
22. Duerig TW, Bhattacharya K. The Influence of the R-Phase on the Superelastic Behavior of NiTi. Shape Mem Superelasticity. 2015;1(2):153–61.
23. Ha JH, Kim SK, Cohenca N, Kim HC. Effect of R-phase heat treatment on

torsional resistance and cyclic fatigue fracture. J Endod. 2013;39(3):389–93.

24. Martins JNR, Nogueira Leal Silva EJ, Marques D, Ginjeira A, Braz Fernandes FM, De Deus G, et al. Influence of Kinematics on the Cyclic Fatigue Resistance of Replicalike and Original Brand Rotary Instruments. J Endod. 2020;(Online):1–8.

25. Wu RCT, Chung CY. Differential scanning calorimetric (DSC) analysis of rotary nickel-titanium (NiTi) endodontic file (RNEF). J Mater Eng Perform. 2012;21(12):2515–8.

26. Elsewify TM, Saber SM PG. Cyclic fatigue resistance of three heat-treated nickel-titanium instruments at simulated body temperature. Saudi Endod J. 2020;(3):8–13.

27. Craveiro De Melo MC, De Azevedo Bahia MG, Buono VTL. Fatigue resistance of engine-driven rotary nickel-titanium endodontic instruments. J Endod. 2002;28(11):765–9.

28. Cheung GSP, Darvell BW. Low-cycle fatigue of NiTi rotary instruments of various cross-sectional shapes. Int Endod J. 2007;40(8):626–32.

29. Ray JJ, Kirkpatrick TC, Rutledge RE. Cyclic Fatigue of EndoSequence and K3 Rotary Files in a Dynamic Model. J Endod. 2007;33(12):1469–72.

30. 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.

31. Ferreira F, Adeodato C, Barbosa I, Aboud L, Scelza P, Zaccaro Scelza M. Movement kinematics and cyclic fatigue of NiTi rotary instruments: a systematic review. Int Endod J. 2017;50(2):143–52.

32. El-din S. ht Factors influencing the fracture of rotary nickel titanium instruments fo r Q ui ot fo r. 2008;2(4):273–83.

33. Saber S eldin. Factors Influencing the Fracture of Rotary Nickel Titanium Instruments. Review article. Endod Prac. 2008 Apr 2;

34. Pedullà E, Ambu E, Rovai F, Chang SW, Campedelli F, Corsentino G, et al. Influence of proper or reciprocating optimum torque reverse kinematics on cyclic fatigue of four single files. J Investig Clin Dent. 2019;10(3):e12409.