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Static and Dynamic Cyclic Fatigue Resistance of Nickel-Titanium Rotary Instruments in a Double-Curved Stainless Steel Artificial Canal

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Abstract: The present study aims to measure the number of cycles leading to fracture (NCF) of instruments in static and dynamic cyclic fatigue situations under body temperature in stainless steel double-curved canals. The framework was constructed to establish the movement of instruments occurring at a stable body temperature. A step motor, a holding system for an endodontic handpiece, created the movement in and out of the artificial canal of the file mounted on the handpiece. A total of 30 instruments of ProTaper Universal and ProTaper Next (Dentsply Sirona, Maillefer, Ballaigues, Switzerland) were divided into three groups of 10 per group. For group 1 (10 PTU F2), files were rotated in static cycles. For groups 2 (10 PTU F2) and 3 (10 PTN X2), files were rotated in dynamic cycles. Files were rotated using proprietary programs, and the times the files were rotated before fracture were recorded. Data were analyzed using survival probabilities and regression with life data. The ProTaper Next in the dynamic cycles had the largest NCF, and the ProTaper Universal in the static condition had the least. New modes of rotation, material, and design have affected the cyclic fatigue resistance of the instrument.

Keywords: cyclic fatigue; dynamic and static test; nickel-titanium; continuous rotation

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1. Introduction

Since introducing nickel-titanium (NiTi) to dentistry, the material, design, and modes of movement for endodontic NiTi instruments have been improving in an endless "In search of excellent" process [1]. NiTi instruments help clinicians overcome complicated issues in modern endodontic therapy, especially concerning root canal preparation [2], in addition to advancing endodontic materials [3,4]. The most troublesome feature of this elastic rotary instrument concerns a fracture during root canal preparation with no visible or precautionary signs [5]. Many elements regarding a complicated mechanism influence the breakage of instruments in the root canal enlargement phase of endodontic therapy [6].

There are two causes for a continuously rotated instrument fracture, relating to the fatigue of the material: one is torsional, and the other is cyclic. When the tip of the file is stuck in the canal, the remaining section of the file is still freely movable, the torsional resistance of the instrument reaches the threshold, and the file breaks [7]. Concerning cyclic failure, the instrument has to bear the repeated loads in a tensile and compressive way when it is freely rotated in the curved canal, and it will fracture when the threshold of cyclic fatigue is over [7].

With the advancements of technologies in different stages from designation to production, such as cross-sectional design, metallurgy, production, before or after surface treatment, thermal process, mode of rotation, endodontic NiTi instruments have been developed continuously to improve cyclic fatigue resistance [6]. Manipulation of NiTi endodontic instruments with dynamic movement is advocated to reduce the proportion of instrument failure during root canal preparation [6].

To simulate the clinical setting, many offers have been recommended and conducted in previous studies [8–14]. Not only is the cyclic fatigue resistance of root canal instruments addressed in these static situations, but also the dynamic condition [2] in both in-and-out or pecking movements is tested [2,11,15]. The static situation has some positives, and outcome results are invaluable, but it does not replicate the actual clinical condition and appears to reduce the cyclic fatigue resistance of the instruments [16]. The dynamic framework, therefore, is more appropriate than the former for the fatigue experiment [16].

The stainless steel artificial canal and other devices have been commonly used in many previous studies [16,17]. Although there are recognized standard requirements for the testing of endodontic instruments by international organizations, these standards have been applied only for standard instruments with a taper of 2%. In particular, these criteria have not included the cyclic fatigue resistance of the instrument [18]. The important shortcoming of the inside diameter of the tube that the instrument rotates in and the fitness of the instrument was mentioned in a previous review [17]. Although many valuable results of the previous studies have added considerable knowledge to the dental literature, there are many factors embedded in the designs of the previous studies that produce conflicting results related to these investigations [17].

Differential scanning calorimetry (DSC) investigation of a nickel-titanium material reveals the phase transformation temperatures and other characteristics, such as phase compositions, amount of endothermic peaks, and enthalpy changes [19]. Not only are the phase components of an instrument important factors, but also the phase transformation temperatures identify whether the austenite, martensite, or both, are dominant in working conditions, determining the instrument's characteristics in the clinical setting [18,19]. Therefore, in addition to the framework with the dynamic situation function mentioned earlier, the proper environment temperature has to be integrated into the framework of any cyclic fatigue resistance testing apparatus to correctly evaluate the properties of the endodontic instrument in correlation with the phase transformation temperatures of the material of the instrument in the study [16,18].

The ProTaper Universal (PTU) and the ProTaper Next (PTN) (Dentsply Sirona, Maillefer, Ballaigues, Switzerland) are two brands from the same manufacturer that have been familiar with clinicians for a long time [20]. These two instrument systems have different materials and designations representing different generations, symbols, and technologies. The conventional NiTi material (PTU), made of the austenitic phase of NiTi alloy, can be transformed into the martensitic phase by stress or external force and can return to the original shape of the instrument after being distorted at the body temperature [21]. Because of the reversible thermoelastic martensitic transformation, the flexibility of the NiTi instrument is much better than the stainless steel instruments. Along with the special convex triangle cross-sectional design, the PTU has a negative rake angle and considerable core diameter that enhance its longevity and safety in clinical treatment. However, the multiple files design of the PTU system prevents it from becoming a popular instrument in endodontic therapy, although this concept is an appropriate approach for students in preclinical education. The material of PTN, M-wire, is the product of the heat treatment process involving conventional NiTi alloy, which changes the phase transformation temperature of the NiTi alloy, enhancing its cyclic and torsional fatigue resistance. The rectangular cross-sectional design with the off-center feature and the reduced files of the system are special characteristics that the manufacturer claimed for the enhanced capabilities of the instrument in higher cyclic fatigue resistance and effectiveness in the curved canal [21].

Although there are many studies on cyclic fatigue resistance at body temperature under both static and dynamic conditions, there is no investigation of the double-curved canal at body temperature under both static and dynamic conditions.

The present study aims to measure the number of cycles until fracture (NCF) of instruments in static and dynamic cyclic fatigue situations, in a body temperature environment, in the stainless steel double-curved canals.

2. Materials and Methods

The sample size of the experiment was calculated using the GPower (3.1.9.7, Universitat Kiel, Dussendorf, Germany) with the power of 0.9, $\alpha = 0.05$, and the effect size of 1.6. The result of the sample size was 10 files for each experimental group. A total of 30 NiTi files, 20 instruments of ProTaper Universal F2 (Dentsply Sirona, Maillefer, Ballaigues, Switzerland), 10 instruments of ProTaper Next X2 (Dentsply Sirona, Maillefer, Ballaigues, Switzerland) with the length of 25 mm for the instruments were included in the present study. All instruments were unused and new as delivered. Instruments were evaluated using a dental operating microscope at a magnification of 10 (CJ Optik GmbH & Co. KG, Aßlar-Werdorf, Germany) concerning any deformations or imperfections on the surface, including the edge and the flute, along the length of the instruments.

A framework, including a gear for holding the endodontic handpiece (X-Smart Plus, Dentsply Sirona, Maillefer, Ballaigues, Switzerland), and a glass box of sewing machine oil (Shell Morlina 10, Shell Corp., Ho Chi Minh City, Viet Nam) containing the artificial canal was constructed to evaluate the cyclic fatigue resistance of the instruments.

For the static cycles experiment, the files of group 1 (10 PTU F2) rotated at the full length of the artificial canal until they broke.

A step motor drove a screw that moved the gear containing the endodontic handpiece. This step motor was controlled by a programmable module that might change or control the motion of the gear as desired. The step motor had a specification of 1.8°/step, needing 200 steps to complete a full rotation of 360°. The pitch of the lead screw of the framework was 5 mm.

The digital controller was set to move the stainless steel block containing the double-curved canal following the desired modes. For the dynamic cycles, the files of the two groups, group 2 (10 PTU F2) and group 3 (10 PTN X2), were used for the experiment. The motion mode was set as in-and-out with a fixed distance until the instrument broke.

A body temperature environment was created using sewing machine oil to sustain the temperature and lubricate the instrument in a glass box. The temperature (37 °C ± 0.5 °C) of the glass box was maintained using a thermostat and heating device.

The stainless steel block containing the artificial canal was produced using a special technique for the double-curved canal with technique parameters, as described elsewhere [22]. The entire length of the artificial canal was 18 mm with a diameter of 1.5 mm. There were two curved segments along the length of the stainless steel canal. The first curved segment's center was at 2 mm from the apex with the angle and the radius of 70° and 2 mm, respectively. The second curved segment's center was at 8 mm from the apex with the angle and the radius of 60° and 5 mm, respectively. In the sewing machine oil, the artificial canal was immobile. The handpiece of the endodontic motor was fixed on the gear designed especially for the X-Smart Plus (Dentsply Sirona, Maillefer, Ballaigues, Switzerland). The gear can be displaced in or out at any distance for each kind of motion, programmed by the operator for control through a liquid crystal display (LCD) interface with function keys.

A stopwatch was placed next to the glass box, and a digital camera Canon 70D (Canon, Tokyo, Japan), was used to capture the entire process from the beginning of movement until the instrument's fracture. The time was recorded for the rotation of the intact file and multiplied by the round per minute (RPM) of each kind of instrument, as instructed by the manufacturer, for the number of cycles. The phase at which the file fracture occurred was recorded whether it happened during the in-or-out phase or at the full length of the canal.

The fragments of instruments were ultrasonically cleaned in 90% alcohol for 15 min before they were sent to the laboratory for observation under an electronic scanning microscope (SEM).

The coronal surfaces of fragments were evaluated under the SEM (JEOL, SM-6510LV; JEOL Ltd., Tokyo, Japan) to observe and capture the microphotograph. The fractography of the breakage surface was described. The data were analyzed for distribution, survival probability, and regression with life data using the Minitab version 19.0. (Minitab, Chicago, IL, USA).

3. Results

The data were checked for distribution using the distribution analysis in Minitab. All data of the three groups have a normal distribution, and the Goodness-of-Fit data of each group are displayed in Table 1.

Table 1. The Goodness-of-Fit of the three experimental groups.

Goodness-of-Fit Anderson-Darling	PTU Static Cycles	PTU Dynamic Cycles	PTN Dynamic Cycles
Weibull	1.727 *	1.494	1.496 *
Lognormal	1.818	1.484 *	1.500
Exponential	3.120	3.171	3.891
Normal	1.739	1.526	1.518

* The smallest value among all the 4 distributions of the same group; therefore, that is the best distribution for that data in the group.

The Weibull distributions best fit the data in group 1 and group 3.

The Lognormal distribution best fits the data in group 2.

These identifications should be used for distribution analysis for each experimental group.

The number-of-cycles file rotated to fracture (NCF) of each instrument system is displayed in Table 2.

Table 2. Median and Interquartile Range (IQF) of NCF for the three experimental groups.

File Systems	Static Cycles		Dynamic Cycles	
	Median	IQR	Median	IQR
PTU	95.957 [a]	43.065	472.142 [b]	216.185
PTN	-	-	895.847 [c]	253.812

[a, b, c] Different superscript letters show significant differences ($p < 0.05$) in the same row and column.

There were significant differences among the three experiment groups in the means of NCF of the instruments. The NCF of PTN in the dynamic situation was the highest, and that of PTU in the static situation was the lowest.

The number of broken segments for the three experimental groups is displayed in Table 3.

Table 3. The number of broken segments for each group.

Groups	PTU Static Cycles	PTU Dynamic Cycles	PTN Dynamic Cycles
Amount	10	10	12

$p > 0.05$.

There was only one fracture point in the PTU groups in both static and dynamic situations. Two PTNs had two fracture points in the PTN group.

Using the distribution analysis of the Minitab, the survival probabilities of the instrument systems are displayed in Table 4.

The survival probability of PTN in the dynamic situation was the best at an NCF of 720, and that of PTU in the static condition was the worst.

In- or out-phases where the file broke in two instrument systems in the dynamic cycles are displayed in Table 5.

Table 4. Survival probabilities of experimental file systems.

	Static Cycles	**Dynamic Cycles**	
File Systems	**PTU**	**PTU**	**PTN**
NCF	90	360	720
Probabilities	0.573	0.789	0.811

NCF: Number of cycles-to-fracture.

Table 5. Phases when the file fracture happened.

Phase	**Dynamic Cycles**	
	PTU	**PTN**
In	2	1
Out	0	2
At the full length	8	7

$p > 0.05$, Fisher Exact test.

There was no significant difference between the two experimental groups in the phase when the file fracture occurred.

The normal distribution should be used for the regression with life data, and the result is displayed in Table 6.

Table 6. Regression table for brand and condition of rotation.

Predictor	**Coefficient**	**Z**	***p***	**95.0% Normal CI Lower**	**Upper**
Intercept	95.479	2.15	0.031770389538 *	8.32933	182.629
Brand					
PTN	385.757	6.13	0.000000000854 *	262.509	509.005
Condition					
Dynamic	403.846	6.42	0.000000000134 *	280.598	527.094

Brand: PTU or PTN. Condition: Static or Dynamic cycles. * $p < 0.05$

There were significant differences among the brands and conditions of the continuing rotation of the instruments. The coefficients were positive, which means the NCF of PTN was higher than that of PTU, and the dynamic condition enhanced the lifetime of the instruments more than the static condition did.

The SEM images of fracture surfaces are displayed in Figures 1–3.

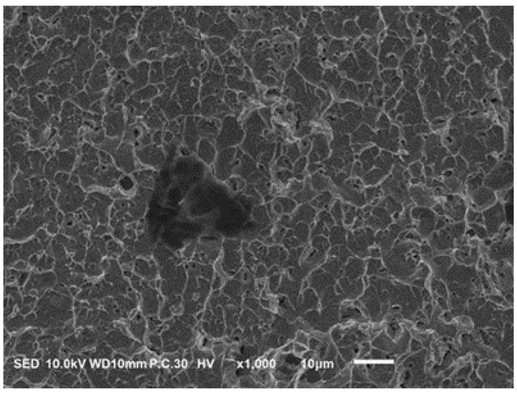

Figure 1. The SEM surface of PTU in static cycles. There is no striation on the entire image.

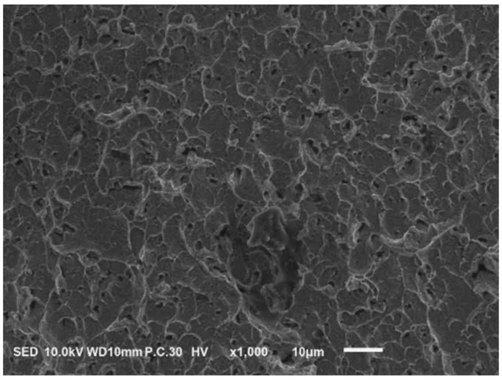

Figure 2. The SEM surface of PTU in dynamic cycles. There is no striation on the entire image.

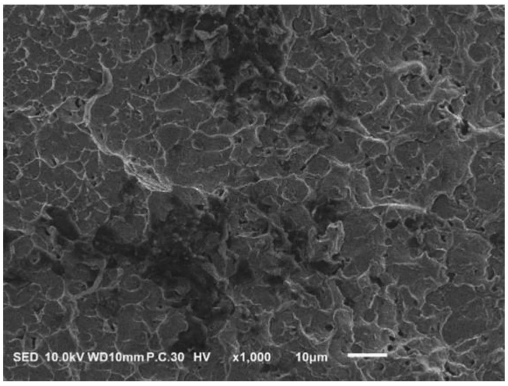

Figure 3. The SEM surface of PTN in dynamic cycles. There is no striation on the entire image.

4. Discussion

The results of the present study show that the NCF of PTN in the dynamic condition is the largest among the three experimental groups. The material, design, and the mode of the dynamic movement of the PTN might be the reasons for the significant difference in NCF among the three groups. Using the distribution analysis in the Minitab, the survival probabilities of PTU and PTN in the dynamic condition are about 80% at the NCF of 360 and 720, respectively. In the static condition, the survival probability of PTU is smaller than 60% at the NCF of only 90. This result supports the concept of dynamic manipulation of endodontic rotary NiTi instrument for enhancing the lifetime of the instrument.

The data in each group have normal distribution when analyzed by the distribution function of the Minitab. However, the best distribution in all four distributions should be selected for further analysis using the Minitab. This is an important issue that facilitates and ensures the accuracy of further statistical analysis.

The phase when the file is broken seems an important factor under the conditions of the present study. This phenomenon is not mentioned in any previous studies. For the present study, almost all fractures occurred when they were at full length inside the artificial canal. Two PTN files were broken in the out-phase of the dynamic situation. In contrast, the fractures of the PTU files occurred at the full length of the canal or the in-phase in the same dynamic condition. Although this difference is not significant in the present study, this result warns the clinician concerning the manipulation of the instruments in a real clinical setting.

The results also reveal that there is only one fracture segment for PTU in both the static and dynamic conditions in the present study, although the double-curved artificial canal was used for the present study. This result differed from previous studies [22–24]. The oil environment, body temperature, material, and design of the PTU could be the factors that influence and change the results of the present study. This result reveals that the two-millimeter apical third of the PTU and PTN hardly broke in the condition of the present study.

The regression with life data shows that the NCF of the PTN was significantly higher than that of PTU because of $p < 0.05$, and the coefficient was positive. The regression table also reveals that the dynamic movement of the file elongated the NCF of the instrument much longer than the static condition because of $p < 0.05$, and the coefficient was also positive. This result supports the concept of the dynamic movement of an endodontic instrument whenever it is inside the root canal.

The reliability/survival function in the Minitab is an alternative approach for the statistical analysis method of the cyclic fatigue resistance experiment. The failure time in this kind of investigation is the exact recorded time when the instrument failed, not right censoring or arbitrary censoring, as identified in the Minitab guidelines. This statistical method offers the options of four distributions. It analyzes the data as identified by the user based on the lowest Anderson-Darling value from the analysis results. The regression with life data offers significant differences, if present, between the different brands of products and between the static or dynamic situations when the experiment is performed. *p*-values and positive or negative coefficients are important values for determining the differences between the experimental groups.

The time recorded from the beginning of rotation to the fracture of the instrument seems more suitable and significant than the RPM to the clinician. However, because of the difference in the RPM for each unique instrument system, the manipulation of time-to-fracture is not fair for an instrument with a higher RPM. Therefore, the comparison of time required to fracture is not suitable for this type of investigation.

The most important problem whenever an artificial stainless steel canal is used for cyclic fatigue resistance experiments is the hardness of the steel used for constructing the canal. If the hardness of the steel is not high enough, the file will damage the canal wall, especially the conventional NiTi alloy used in PTU. Therefore, it is hard to maintain the original geometry of the artificial canal, resulting in an improper outcome. Because of the unsuitable movement distance of the instrument inside the steel canal, the time-to-fracture of the instrument will be shortened or elongated, leading to the incorrect result.

The endodontic motor used in the present study shows that it will stop suddenly with no premonitory signals. Perhaps this is a protective function of the manufacturer. In the pilot study, the motor stopped in certain situations. However, with a proper room temperature between 20 °C and 23 °C, the endodontic motor did not stop during the testing period, assuring reliable results.

The body temperature nowadays is the standard factor of the environment for cyclic fatigue or torsional resistance experiments [16]. The environment might be controlled for a small space, such as the stainless steel canal block [9] or the bath of water or saline containing the metal canal block [10]. The other way to simulate the clinical situation with the body temperature of the environment for the experiment is to control the room temperature. However, high temperature is improper for the sensitive endodontic motor, handpiece, and the operator.

Although the temperature of the inside root canal could reach the body temperature with the presence of the hypochlorite sodium from the room temperature when the cyclic fatigue resistance testing was performed [25], this unstable temperature is hard to maintain, and there is nothing to ensure that this body temperature could be reached at the very beginning of the experiment when the instrument rotates.

Lubrication of the artificial canal is another important factor in the experiment. A lubricant displayed in a spray bottle changes the temperature of the artificial canal rapidly and affects the phase transformation of the material, resulting in an incorrect outcome. The option of sewing machine oil for lubricating and maintaining the temperature of the experimental environment is more appropriate than the option of spray oil. Spray oil has certain disadvantages, such as the amount of oil being modest for each use and the rapid reduction of the device temperature. This machine oil is odorless, colorless, and tasteless, resulting in the proper background for capturing the motion. The oil bath in the box serves as the irrigation environment, in that the irrigation solution is fully filled inside the root canal.

A heating oil device can be easily equipped along with the temperature controller, resulting in a stable temperature system for the present experiment.

For the S-curved artificial canal, the position of the breakage on the apical third of the instrument is popular, although, in the pilot study, there were some circumstances in which the second curved position fracture came first, a rare phenomenon that still occurred. This phenomenon might have resulted from the design and material of the PTU, which facilitate the fracture of the file happening in the second curvature from the apex of the double-curved canal. This could be a benefit of PTU because the longer the fracture segment in the S-curved canal, the easier the removal procedure. Perhaps under other situations, there will be an unusual fracture of the file. Unfortunately, for most circumstances in the clinical situation, the shorter the breakage segment is, the harder the removal procedure.

The SEM image of the breakage surface shows no striation on the investigated area that existed on the figure, as reported in the previous study [26]. There is the same pattern on the breakage surfaces of the three experimental instruments at the magnification of 1000. Fatigue fracture without striation might happen in some situations [8,27,28]. Creep fatigue interactions could contribute to the mechanism in the formation of the fractography of fracture surface without striation under the situation of the present study [28]. This result differs from that of the previous study [26]. This difference comes from the oil environment surrounding the artificial canal and the temperature reaching body temperature, simulating the clinical condition.

The present study did not evaluate the cyclic fatigue resistance of endodontic instruments in different modes of in-and-out movement, and the framework was designed just for body temperature. The room temperature was not tested in the present study; therefore, it could not contribute to the knowledge of the decrease of NCF in the high-temperature environment in a certain study on cyclic fatigue resistance [29].

The instrument systems used in the present experiment represent conventional materials, although the M-wire of PTN is still new in contemporary endodontic therapy. Both materials of the two instrument systems have an austenite start temperature above body temperature. Future studies should be conducted to investigate the differences among different materials with lower austenite start temperatures at different environmental temperatures.

However, the weakness of the present study, still present today, should not go unmentioned. Regardless of whether the instruments are used statically or dynamically and whether they are as close as possible to the clinical situation, the existing models could not achieve effective loading through actual ablation and the resulting friction in the root canal. This could reduce the number of cycles-to-fracture of the experimental instruments.

Further investigations should be performed to evaluate the cyclic fatigue resistance of other endodontic instruments in different rotation modes with different movement distances. Other curved parameters and locations should be performed on the framework to cover more circumstances simulating the clinical situation.

5. Conclusions

Under the conditions of the present study, the framework ensures a stable body temperature for the environment along with the oil bath for maintaining suitable lubrication of the instrument movement inside the double-curved stainless steel artificial canal. The dynamic situation significantly enhances the lifetime of the continuous rotary NiTi instruments regardless of material or design. The ProTaper Next in the dynamic cycles had the largest NCF, and the ProTaper Universal in the static condition had the smallest value. New materials and designs have affected the cyclic fatigue resistance of endodontic instruments.

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