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The Role of Pecking Motion Depths in Dynamic Cyclic Fatigue Resistance: In Vitro Study

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A B S T R A C T

Objective: This is the first study evaluating the impact of different pecking motion depths on dynamic cyclic fatigue resistance of different endodontic instruments.
Methods: Four nickel-titanium systems (Hyflex EDM OneFile 25/. ~; Rotate 25/0.6; Mtwo 25/0.6; Reciproc Blue R25) were tested. Forty instruments from each group were subjected to 4 different pecking movements to evaluate their cyclic fatigue resistance. The distances for the pecking motion were 3-mm forward and backward, 1-mm (3-mm forward and 2-mm backward), 2-mm (4-mm forward and 2-mm backward), and 3-mm (5-mm forward and 2-mm backward). Speeds were 100 and 200 mm/min for the descending and ascending motion, respectively. The times to fracture (TtF) in seconds were recorded for each instrument. Data were statistically analysed by using 2-way ANOVA and Bonferroni multiple comparison post hoc test ($P < .05$).
Results: All instruments had a significant increase in cyclic fatigue resistance during the forward dynamic motion compared with the axial continuous. Overall, the heat-treated instruments reported higher fatigue strength than the untreated files ($P < .05$). Reciproc Blue and Hyflex EDM showed higher TtF in the forward movements of 1-/2-mm and 2-mm ($P < .05$), respectively while Mtwo 25.06 and Rotate 25.06 in the forward movement of 3-mm ($P < .05$).
Conclusions: Within the limits of this in vitro study, the pecking motion depths had varying impacts on the cyclic fatigue resistance of instruments. Reciproc Blue and Hyflex EDM performed significantly better with pecking motions of 1-and 2-mm. Improving endodontic instrument durability through specific pecking depths has the potential for improving clinical performance and reducing instrument failures.

Introduction

Nickel-titanium (NiTi) instruments can fracture due to torsional failure or cyclic fatigue.[1-3] Torsional overload is caused by the locking of endodontic files during rotational movement.[4] Cyclic fatigue occurs when a NiTi endodontic instrument rotates in a curved root canal.[4] During rotation, the structure of the endodontic instrument is alternately subjected to cycles of compressive and tensile stress, which produce microstructural changes causing the breakage of the rotating endodontic file.[5]

Failure due to cyclic fatigue is particularly dangerous not only because of the frequency with which occurred, but also because of its clinical implications.[6] Instrument design, kinematics, and shaping procedure are some of the main factors influencing the cyclic fatigue resistance of NiTi rotary instruments.[4]

The Hyflex EDM OneFile (HEDM, Coltene/Whaledent AG) is an instrument designed to shape root canals using a single-file technique in continuous rotation.[2] It is made of a controlled memory alloy with a constant taper of 8% in the apical 4-mm which decreases to 4% toward the coronal region. The operative part of the file is characterized by 3 different horizontal cross-sections.[7-9] Mtwo (VDW) is a continuous rotating

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instrumentation made of conventional NiTi alloy with an S-shaped cross section.[10] Rotate (VDW) is a new continuous rotary system created with the aim to update the Mtwo sequence using a reduced number of instruments and heat-treated post-processing alloy.[10] Reciproc R25 (VDW) has been upgraded to Reciproc Blue by using an innovative heat treatment that modifies the molecular structure of the alloy and gives the instrument a blue colour.[11]

To limit the instrument fracture's risk, an in-and-out motion, also known as pecking motion, has been recommended during the rotation of the NiTi file. This motion opposes the screwing forces generated during the file rotation in a controlled mode.[12]

Tests for cyclic fatigue resistance can be static (as most studies are) or dynamic. In static, the instrument is inserted into the simulated root canal to a certain depth and rotated without further movement until file fracture occurs. The static model generates the maximum bending stress at the centre of the curve.[13] In dynamic cyclic fatigue tests, the file is moved within the simulated root canal with a certain amplitude to simulate the clinical situation.[14-16] These movements give the file a longer time interval before it passes back through the area of greatest stress, increasing the time until file fractures.[1,17] Therefore, the use of pecking motion during instrumentation with NiTi motor-driven rotating instruments should significantly extend instrument's life.[6]

Currently, no studies examined the effect of different pecking depths on dynamic cyclic fatigue resistance of NiTi instruments such as HEDM, Rotate, Mtwo, and Reciproc Blue.

Therefore, the purpose of this study was to evaluate the influence of different pecking motion depths on the cyclic fatigue resistance of HyFlex OneFile 25/.08 ~, Rotate 25.06, Mtwo 25.06, Reciproc Blue R25 endodontic instruments.

This research is clinically relevant as it investigates how varying pecking motion depths (i.e., differential depth of forward and backward motions) can affect file durability in conditions that closely simulate real-life usage. Since no existing studies have assessed this specific aspect, our findings will fill a significant gap in the literature and provide new insights that could lead to more effective and safer clinical practices. This study could fundamentally enhance the understanding of NiTi file endurance, ultimately contributing to the advancement of endodontic treatment outcomes.

The null hypotheses were that (1) the different pecking motion depths would not affect the cyclic fatigue resistance of the tested instruments and (2) the different instruments would not differ in terms of cyclic fatigue resistance when tested at the same pecking depth.

Materials and methods

With a sample size of 160 instruments, a number of 4 groups, a power of 0.80, and $\alpha = 0.05$, the present sample size was adequate to detect a minimum effect of f = 0.32. The analysis was performed with G*Power 3.1 for Macintosh (Heinrich Heine, Universität Düsseldorf).

Hyflex EDM OneFile 25/. ~, Rotate 25/.06, Mtwo 25/.06, and Reciproc Blue R25 were used in this study. For each NiTi rotary system, 40 new 25-mm-long instruments were selected. The files in each NiTi rotary system were further divided into 4 groups to conduct dynamic cyclic fatigue tests with different pecking depths (n = 10 per group). Each instrument was inspected for defects or deformities before the experiment under a stereomicroscope (SZR- 10; Optika); none was discarded. Cyclic fatigue testing was performed using a custom device previously described.[18] The electric handpiece with 6:1 reduction (Sirona Dental Systems GmbH) was maintained in a fixed 3-dimensional position with a mobile rail support allowed for standardized insertion/withdrawal of the file within the artificial canal.[18] A simulated 16-mm long stainless-steel artificial canal with a 60° angle and a 5-mm radius of curvature was used.[18] In addition, the artificial canal was connected to a thermostat to maintain a constant temperature of 35°C ±1°C in all tests.

The 4 NiTi systems were divided into 4 groups activated in different dynamic motions. In group 1, the instruments were positioned up to 3-mm from the apex of the canal and were tested with a continuous dynamic axial (forward and backward) movement of 3-mm/s (classic dynamics). In groups 2, 3, and 4, the instruments were tested with a dynamic (pecking) forward motion of 1-, 2-, and 3-mm, respectively. In the group with pecking depth of 1-mm, the files were placed at the beginning of the curve of the artificial canal (8-mm from the apex) and penetrated 1-mm in the apical direction with each pecking movement of 3-mm forward and 2-mm backward. The files, once they reached the apex, returned to the starting point to repeat the movement until they broke. Similarly, movements of 4-mm forward and 2-mm backward,[12] and 5-mm forward and 2-mm backward, resulted in an advancement of 2-mm and 3-mm, respectively.

Using a torque-controlled endodontic motor (Reciproc Gold; VDW) and following the manufacturers' instructions, NiTi rotary files were rotated freely in the root canals until fracture occurred.[19] Hyflex EDM were rotated at 400 rpm and maximum torque 2.5 Ncm; Rotate (VDW) and Mtwo instruments were rotated at 300 rpm and 280 rpm, respectively, both at 2.3 Ncm; Reciproc Blue R25 files were used with the ''Reciproc ALL'' program until fracture occurred. A speed of 100 mm/min was employed for descending and 200 mm/min for ascending.[19]

A specific high-flow synthetic oil (Super Oil; Singer Co Ltd.) was applied to decrease the file friction on the artificial canal walls.

The times to fracture (TtF) were recorded in seconds for each instrument tested with a digital stopwatch.[20,21] A digital camera was used to confirm the data.

The fractured fragment length of each instrument was measured with a microcalliper, and then the fractured surfaces were examined with the Scanning Electron Microscopy (SEM) device (ZEISS Supra 35VP; GmbH) at different magnifications (× 475 to × 800) (n = 2, each).

Statistical analysis

Normality of data was assessed by the Shapiro-Wilk test. Once their normality was confirmed, the data were statistically analysed by using 2-way ANOVA and the Bonferroni multiple comparison post hoc test (Prism 8.0; GraphPad Software, Inc.). Statistical significance was set at 95% ($P < .05$).

Results

The means and standard deviations of the TtF values of the various instruments tested at the different pecking depths are shown in Table.

Comparison of the different peckings

All instruments had a significant increase in cyclic fatigue resistance during forward dynamic movements compared to the axial continuous dynamic motion ($P < .05$). Particularly, the HEDM instruments showed the highest resistance during pecking of 2-mm forward and the lowest with classical dynamics ($P < .05$). Cyclic fatigue resistance of HEDM at 1-mm was significantly higher compared with 3-mm ($P < .05$).

The TtF values of the Rotate 25.06 were significantly higher at 3-mm pecking followed by 2-mm, 1-mm, and classical dynamics ($P < .05$).

The Mtwo 25.06 showed significantly higher TtF at peckings of 3-mm, followed by 1-/2-mm and classic dynamics ($P < .05$). Reciproc R25 Blue instruments showed significantly higher Ttf at peckings of 1- and 2-mm when compared with the other depths tested ($P < .05$), with 3-mm performed significantly better than classic dynamics ($P < .05$).

Comparison of the different instruments

The Reciproc R25 Blue had the highest TtF in classic dynamics ($P < .05$), followed by HEDM/ Rotate 25.06 and Mtwo, with no significant difference among the HEDM and the Rotate 25.06 ($P > .05$).

The Reciproc R25 Blue showed statistically higher fatigue resistance than the other instruments at 1-mm pecking ($P < .05$), with no significant difference between the HEDM and the Rotate 25.06 as well as between the Rotate 25.06 and the Mtwo 25.06 ($P > .05$).

The TtF of the HEDM and the Reciproc R25 Blue were statistically greater ($P < .05$) than those of the Rotate 25.06 and the Mtwo 25.06 during 2-mm pecking, with Rotate 25.06 reporting higher TtF than Mtwo 25.06 ($P < .05$).

In the 3-mm pecking, the Rotate 25.06 and Reciproc R25 Blue exhibited higher statistically difference ($P < .05$) compared with the HEDM and Mtwo 25.06, with no significant difference between the Rotate 25.06 and the Reciproc R25 Blue neither between the HEDM and the Mtwo 25.06 ($P > .05$).

The mean length of fractured fragments was not significantly different among the files (5.01 mm) ($P > .05$).

The SEM examination showed that the entire fracture surface was marked by dimples, indicative of repetitive stress fatigue. This dimpled pattern was uniform across all the files we tested, implying a consistent stress pattern that caused them to fail. The presence of such dimples typically points to the area of the material where plastic deformation has occurred and from where crack propagation has initiated, leading to the eventual fracture of the files (Figure).

Discussion

Although the model of the extracted tooth is more similar to the clinical situation, cyclic fatigue resistance was evaluated using a customized device which allowed for a dynamic axial motion comparable to the pecking motion performed by the operator during a root canal treatment in a standardized manner.[4,11]

The choice of instruments also ensured to simulate a clinical context, testing instruments with different design and heat treatment in order to assess their impact during pecking motions.

During rotary instrumentation, NiTi file is subjected to major stress near the shortest radius area of a curved root canal. In this condition, the axial and in-and-out motion of instrument are important characteristics for the distribution of stress concentration during file rotation.[22-25] Within this context, different pecking motion depths were investigated in this study with the aim to determine their impact on cyclic fatigue resistance of different NiTi instruments. For a more accurate representation of clinical scenarios, the ascending speed was adjusted higher than the descending speed. It is common for the withdrawal of the instrument to occur more rapidly than the inward movement, primarily due to the release of resistance during withdrawal.[19]

According to the present results, all instruments had a significant increase in fatigue strength during dynamic movements with pecking depths of 1, 2, and 3-mm compared to continuous axial movement. Thus, the first null hypothesis can be rejected. Specifically, when comparing the different

Table – Mean and standard deviation (SD) of times of fracture (TtF) in seconds (sec) of each tested instrument at different pecking depths.

	Times to fracture (sec)							
	Classic dynamics		Pecking 1-mm		Pecking 2-mm		Pecking 3-mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Hyflex EDM 25.08	165^{a1}	26	625^{b1}	85	818^{c1}	99	482^{d1}	59
Rotate 25.06	201^{a1}	10	500^{b12}	46	585^{c2}	81	649^{d2}	24
Mtwo 25.06	119^{a2}	12	384^{b2}	12	378^{b3}	15	474^{c1}	54
Reciproc Blue R25	248^{a3}	23	771^{b3}	66	735^{b1}	31	612^{c2}	86

Same superscript letters indicate no significant difference between the different tests for the same instrument.
Same superscript numbers indicate no significant difference between the different instruments for the same test.

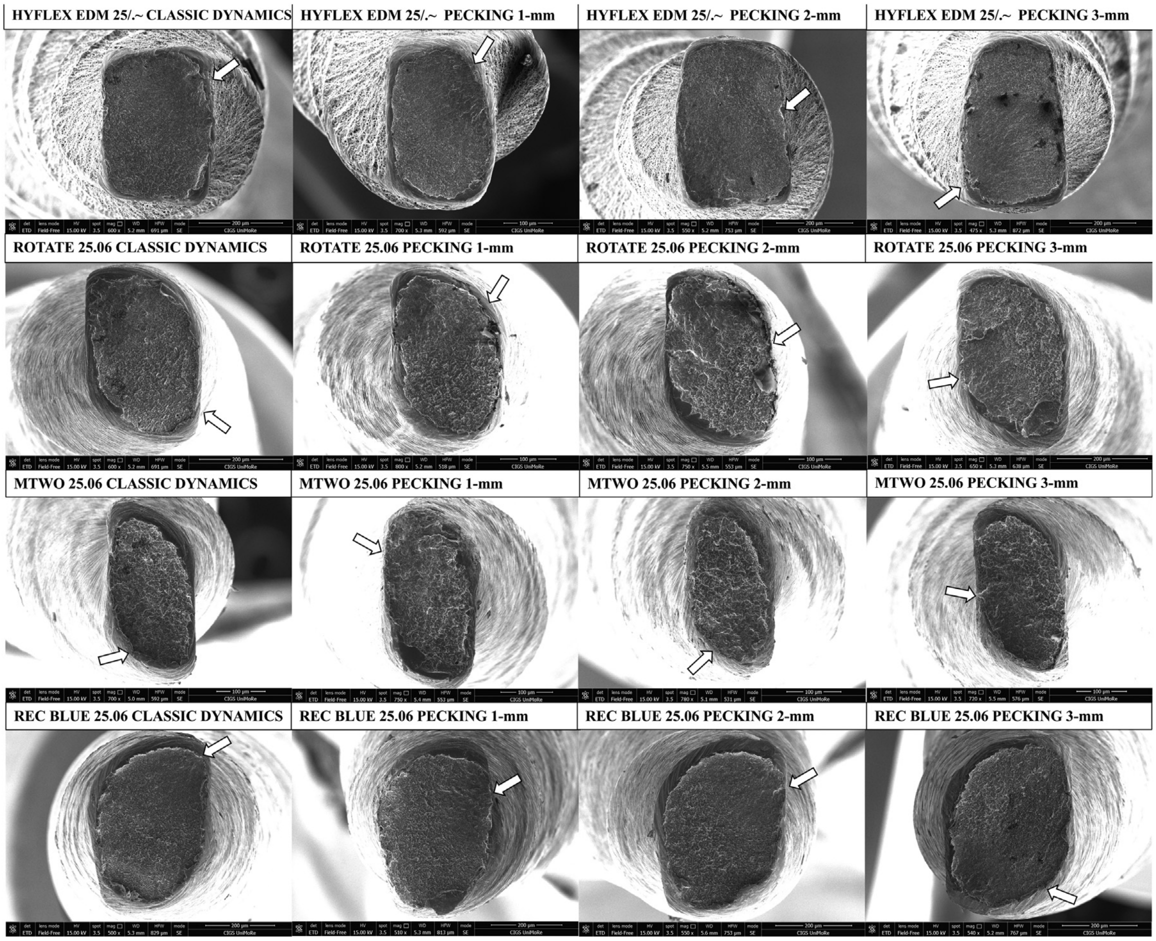

Figure – Scanning electron microscopy images of the fracture surfaces of HEDM files (25/. ~), Rotate 25/0.6, Mtwo 25/0.6 and Reciproc Blue R25 instruments after cyclic fatigue test. The fracture surface shows numerous dimples spread with the white arrows indicating the origin area of the cracks.

types of pecking, the HEDM and the Reciproc Blue had higher fatigue resistance in 2-mm and 1-/2-mm forward motions respectively, whereas the Mtwo 25.06 and the Rotate 25.06 had significantly higher resistance at 3-mm. This result could be due to the different instrument taper. Hyflex EDM and Reciproc Blue have a taper of .08 in the first apical millimetres; conversely, Mtwo and Rotate have a uniform taper of .06. The increased taper in the first 4-mm apical of the HEDM and the Reciproc R25 Blue instruments could result in greater friction with the canal walls during deeper pecking movements compared with less extensive movements. In contrast, the Mtwo 25.06 and the Rotate 25.06 instruments, having a constant taper and smaller diameters in the apical first millimetres of the instrument, may exhibit greater centring within the canal and better stress distribution along the instrument body during 3-mm pecking movements.

Ha et al.[12] conducted studies on the screwing forces experienced by the instruments during pecking movement within the canal, showing that less stress is generated within the instruments and against the canal walls during a shallower pecking depth. Therefore, although the current tests are different from those of Ha et al., it could be hypothesized that instruments with larger taper generate less stress forces inside the canal during shorter pecking movements by increasing their resistance to breakage.

Significantly differences emerged between different instruments at a same pecking depth. Thus, also the second null hypothesis can be rejected. The Reciproc Blue files had significantly higher times to fracture in all tests than the HEDM; only during pecking of 2-mm not significantly difference emerged between the 2 files. The different behaviour may be imputable to the different heat treatment and kinematics employed. The reciprocating motion results in higher cyclic fatigue strength of instruments specifically designed to be used in reciprocating motion. It has been hypothesized that the increase in fatigue strength is due to the release of reaction stresses cumulated in the material with the reversal of the direction of rotation.[26-28] In addition, blue treatment may provide an increase in cyclic fatigue resistance.[29-31] Yet, recent studies comparing cyclic fatigue resistance of Reciproc Blue and HEDM reported contrasting results[7,21] possibly imputable to the different methodological conditions. Because no previous studies compared mechanical behaviour of Reciproc Blue and HEDM at different pecking depths, our findings are not directly comparable with previous investigations. Rotate instruments showed significantly higher cyclic fatigue resistance when compared with Mtwo, as previously reported.[10] In addition, Rotate 25.06 and Reciproc Blue exhibited the highest fatigue resistance among the tested instruments at the 3-mm pecking. This result could be explained by the advantage of pecking depth combined with taper and file's alloys. Interestingly, no significant difference emerged between HEDM and Mtwo at the 3-mm pecking. The pecking pattern combined with geometrical features of Mtwo might contribute to this finding. Further research is needed to confirm these hypotheses.

A recent study[16] evaluated the impact of different pecking amplitudes on the dynamic cyclic fatigue resistance of Mtwo Minimal rotary files reporting that the 3-mm pecking amplitude increased the cyclic fatigue resistance of the smaller instruments. Of note, the 1-mm and 3-mm pecking amplitudes evaluated in that study corresponds to the continuous dynamic axial (forward and backward) movement of classic dynamics that it is different from the differential depth of forward and backward motions in the dynamic model tested in the current study.

In our study, SEM analysis revealed the presence of dimples across the entire fractured surface, a hallmark of cyclic fatigue failure. This pattern was consistent among all the tested files, suggesting a uniform type of stress leading to failure. This finding is in line with the literature, where similar observations of dimples and characteristic beach lines indicative of a fatigue failure have been reported.[32-34] The high magnification capabilities of SEM provide a depth of detail that is not achievable with other imaging modalities, enabling us to discern the microstructural changes and crack propagation patterns which underpin the mechanical integrity of these instruments.

Despite the rigorous methodology, some limitations need to be mentioned. Other factors such as torsional stress and anatomical complexities acting simultaneously during root canal shaping and may impact the clinical performance of NiTi files.[12,32] In addition, the validity of these findings is limited to the laboratory testing conditions such as the type of instruments investigated and pecking depths employed. Furthermore, it is pertinent to acknowledge that while our study primarily focused on the impact of pecking motion depths on the cyclic fatigue of NiTi instruments, the role of irrigation solutions was not explored in this context. Continuous irrigation is known to influence fatigue resistance by reducing stress on canal walls, ensuring a good simulation of clinical conditions compared with the simple immersion techniques.[35,36] The literature suggests that certain combinations of irrigants, specifically NaOCl with etidronate acid (HEBP), can significantly decrease instrument resistance.[37] This underscores the need for thoughtful selection of irrigation solutions in clinical practice. Future research will aim to integrate these variables to provide a comprehensive understanding of their collective impact on endodontic instruments' durability.

Within these limitations, the results are clinically relevant because they confirm as different axial in-and-out depths combined with different instruments may significantly affect the file durability.

This research has established a solid platform for advancing our understanding of the factors that contribute to the cyclic fatigue resistance in NiTi endodontic instruments, setting the stage for more in-depth future investigations in this field. A crucial next step will involve assessing the impact of pecking motion depth under the continuous irrigation conditions that are typical during clinical use. Given the significant influence of irrigation on cyclic fatigue, understanding its interplay with pecking motion depth could yield important insights into optimizing the longevity of these instruments. Future studies will also expand to consider the effects of pecking motion amplitude on instruments with varied dimensions. By investigating how motion amplitude impacts files of different sizes and tapers, it may be possible to generalize the findings of the current study more broadly or to tailor recommendations for the use of specific instrument types. Additionally, incorporating a range of instrument brands into subsequent research is essential for strengthening the conclusions drawn from this study. This diversity will not only reinforce the external validity of the current findings but also ensure that the results are reflective of the performance of the wider array of files available to endodontic practitioners.

Conclusions

Under in vitro limitations, different pecking depths significantly impacted the cyclic fatigue resistance of the tested files. Specifically, Reciproc Blue and Hyflex EDM performed significantly better with short pecking motions of 1-and 2-mm while the Mtwo 25.06 and Rotate 25.06 with 3-mm pecking.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

All authors have contributed significantly and are in agreement with the manuscript.

Conceptualization: Pedullà, Generali
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